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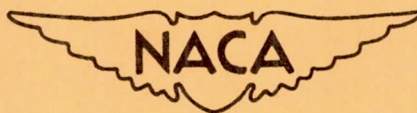
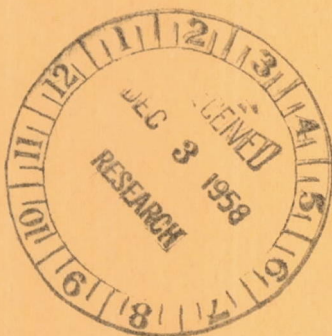
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**SLIP-FLOW HEAT TRANSFER FROM CYLINDERS
IN SUBSONIC AIRSTREAMS**

By Lionel V. Baldwin

Lewis Flight Propulsion Laboratory
Cleveland, Ohio



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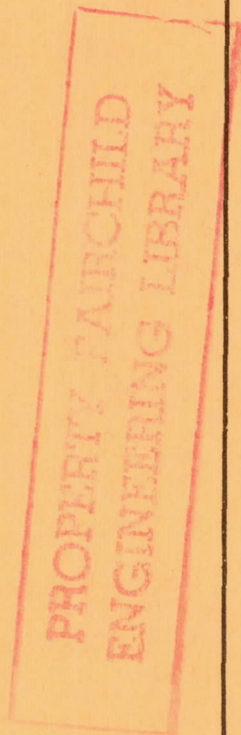


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By Lionel V. Baldwin

SUMMARY

Over 1000 measured convective heat-transfer coefficients for normal cylinders in subsonic slip flow have been correlated by using Nusselt number as a function of Reynolds and Knudsen (or Mach) numbers. The experimental range corresponds to the following dimensionless groups: Mach number M , 0.05 to 0.80; Reynolds number Re , 1 to 75; Knudsen number Kn , 0.009 to 0.077. Air temperatures between 0° and 280° F and cylinder temperatures between 34° and 620° F were used. At $Kn = 0.009$, the Nusselt number (Nu) correlation extrapolated smoothly into continuum-flow empirical curves, which show Nu as a function of $\sqrt{Re}$ with a small, regular variation in Nu from compressibility or Mach number effects. The data showed increasing sensitivity to Kn as it increased to 0.077. The experimental Nu curves at $Kn = 0.077$ qualitatively verified two characteristics predicted by free-molecular-flow theoretical analysis. These are a shift to first-power dependence on Re and large separation of constant Mach number parametric curves due to rarefied gas-flow phenomena. Therefore, the experimental slip-flow correlation served as a bridge between continuum empirical relations and free-molecular theoretical results, but data between $0.10 < Kn < 2$ are required to complete this general correlation.

A complicated nonlinear dependence of the heat-transfer coefficient to the difference between cylinder and recovery temperature ΔT is reported. The heat-transfer coefficient h increased with increasing ΔT for $Kn < 0.02$; while for $Kn > 0.02$, h decreased with increasing ΔT . The Mach number had a secondary effect on this ΔT phenomenon. For cylinders operated at $\Delta T > 200^{\circ}$ F and over the entire range of this research, an increase in air temperature increased the heat-transfer coefficient. The preceding were second-order effects that caused deviations of up to 20 percent from the general correlation.

Finally, the application of these research results to hot-wire anemometry is discussed.

INTRODUCTION

Fine metal wires, 0.00005 to 0.001 inch in diameter, have been widely used in aerodynamic research as anemometers. The use of hot-wire anemometers for mean flow measurements began with the early work of King (ref. 1), while the investigation of fluctuations in airflows started with the classical research of Dryden and Kuethe (ref. 2). In every application, the sensitivity of the electrically heated anemometer to the flow properties is determined by the heat-transfer characteristics of cylinders in forced convection. Assuming potential flow over the wire, King derived an equation for steady flow that relates the electrical power input to the heat loss by convection:

$$I^2 \Omega_w = (A + B \sqrt{U})(T_w - T_a) \quad (1)$$

where

$$A = a l k$$

$$B = b l \sqrt{D_w \rho c_p k}$$

(All symbols are defined in appendix A.) In usual practice, the constants in King's equation, A and B, are obtained experimentally from a calibration curve of $I^2 \Omega_w / (\Omega_w - \Omega_a)$ as a function of $\sqrt{U}$ for each wire used. The sensitivity predicted by King's equation is the basis for hot-wire-anemometer techniques that have become rather elaborate (e.g., ref. 3) in slow subsonic flows.

As aerodynamic research progressed into transonic and supersonic flows, it was natural to investigate the heat-loss characteristics of hot wires and to attempt extension of this research tool. In order to describe the influence of flow parameters over a wide range, recent investigators have used dimensionless groups to generalize heat-loss correlations. Hot-wire heat-loss studies not only supply anemometer sensitivity, but also have furnished the bulk of the heat-transfer measurements for cylinders in slip and near-free-molecule flows. Interest in this phase of aerodynamics has grown greatly as it has become necessary to compute heat transfer to missiles and satellites that fly at high altitudes. Though these objects generally fly at very high speeds, the actual flow over the body is subsonic in many cases, because shock waves occur near forward surfaces. This investigation follows some excellent research in this field during the past eight years; therefore, it is appropriate to outline the problem studied here in terms of what previous workers have established.

Review of Previous Investigations

The Reynolds number (based on cylinder diameter) and Mach number are the usual dimensionless groups chosen to specify the regimes for airflow over normal cylinders. Figure 1 is a convenient summary of recent heat-transfer experiments with normal cylinders. The Mach number of the ordinate is based on free-stream velocity and static temperature; the abscissa is the Reynolds number based on the cylinder diameter and on free-stream density, velocity, and viscosity. The shaded areas indicate the experimental ranges of previous work, and these areas are keyed by numbers to the reference list of this report (refs. 4 to 16). Figure 1 also shows the research region of this paper.

The two constant Knudsen number lines in figure 1 provide a guide to the flow regimes. Though the boundaries of free-molecule, slip, and continuum flows probably are not sharply defined, reference 15 proposed the following definitions for flow over normal cylinders:

- (1) Continuum flow: $Kn < 0.001$
- (2) Slip flow: $0.001 < Kn < 2$
- (3) Free-molecule flow: $Kn > 2$

The Knudsen number Kn is defined as the ratio of the mean free path of the gas λ to the cylinder diameter D_w . Kinetic theory of gases relates the Knudsen number to the ratio of the Mach number to the Reynolds number; for air, this proportionality is as follows:

$$Kn \equiv \frac{\lambda}{D_w} \approx 1.45 \frac{M}{Re_t} \sqrt{\frac{T}{T_t}} \quad (2)$$

At atmospheric pressure with anemometer wires 0.0002 inch or smaller in diameter, the flow region for the hot wires in much of the early turbulence work would fall below M of 0.10 and between Re of 3 and 30.

King's equation can be written in terms of nondimensional groups as

$$Nu = A' + B' \sqrt{Pr} \sqrt{Re} \quad (1a)$$

The 0.5-power dependence on Reynolds number is well established in slow subsonic continuum flows (ref. 11). However, Lowell (ref. 10) was the first to point out that the Reynolds number alone does not correlate fine-wire heat-transfer data over an appreciable velocity range. He reported that the Mach number was a parameter at $M = 0.375$ and 0.575 . Then, Laurence and Landes (ref. 9) found that their data correlated if Nu was plotted as a function of $\sqrt{Re}$, but the Mach number remained a

parameter even in the range of $M = 0.1, 0.2, \text{ and } 0.3$. Since the work being reviewed is limited to room-temperature airflows over cylinders (i.e., viscosity is constant), the use of both Re and M simply shows that ρD_w and U are not interchangeable in the product $\rho D_w U$. This has been noted by later investigators (refs. 12, 14, and 16). It is well established that the maximum separation of the constant Mach number lines on a plot of Nu against $\sqrt{Re}$ occurs at the lowest Mach numbers; in fact, by proper choice of fluid properties, this "Mach number effect" can be almost eliminated in supersonic flow (refs. 7, 8, 14, and 15).

The Knudsen number was introduced as a correlating parameter in reference 14. The effect of ρ and D_w in the product ρD_w was found to be fully equivalent over the wide experimental range of reference 14. Since conditions of constant ρD_w are constant Knudsen number flows, the Knudsen and Reynolds numbers were shown to be the governing parameters in the incompressible range. The nonequivalence of ρD_w and U in attempted Reynolds number correlations was most pronounced for very fine wires that exhibited low sensitivity to velocity.

Nearly all the anemometer heat-loss investigators have varied the operating temperature of the wire (refs. 9, 10, 14, and 16). The most extensive research has been reported by reference 14, which found that the Nu varied with wire temperature at a given flow condition, and that this variation depended on both M and ρ . However, no simple correlation was found to cover all of the effects observed when the wire temperature was varied.

Reference 16 reports measurements of the nonlinear variation with wire temperature of the heat-transfer rate from hot wires from $M = 0.5$ to 2.5 and $Re = 18$ to 144. The reference proposed a nonlinear overheat ratio ξ defined as

$$h = h_0(1 - \xi \bar{a}_w) \quad (3)$$

where h_0 is the heat-transfer coefficient extrapolated to $\Delta T = 0$, and $\bar{a}_w \equiv (\Omega_w - \Omega_e)/\Omega_e$. The overheat ratio ξ was found to be a function of Mach and Reynolds numbers. Like reference 14, reference 16 found that the nonlinearity reverses under some flow conditions. That is, for some Reynolds numbers in the subsonic region the heat-transfer coefficient increased with increasing wire temperature; and, depending on M and Re , the heat-transfer coefficient was observed to decrease with increasing wire temperature under other flow conditions.

The work of reference 16 is the nearest approach to formulating clearly the important parameters affecting the nonlinear variation of heat-transfer rate with wire temperature. However, the results are

limited to transonic and supersonic Mach numbers and to three values of Reynolds number. Additional data are required to verify the predicted trends at lower subsonic Mach numbers.

Objectives of This Research

The primary objective of this research was to examine the nonlinear variation of heat transfer with wire and air temperatures. The effect of wire temperature is complicated and not fully clarified by previous work, while there appears to be no systematic variation of air temperature in heat-transfer experiments from fine wires. Besides providing an additional insight into the nonlinearity of heat transfer with ΔT , data taken at various air temperatures are important for some hot-wire-anemometer applications (e.g., appendix E of ref. 17).

Furthermore, sufficient heat-transfer data from normal cylinders have been published in recent years that it should be possible to show clearly the effect of continuum, slip, and free-molecule flows on heat-transfer characteristics. An attempt to find a preliminary general correlation based on the results of this and earlier work is also an objective of this report.

APPARATUS AND PROCEDURE

Apparatus

Tunnel and air facility. - A sketch of the variable-density, low-turbulence tunnel used in this research is shown in figure 2. The incoming air passed through a cone-shaped filter screen covered with filter paper and wool felt. The air then entered the 6-inch-diameter inlet section where a total-pressure probe and heater control thermocouple were located. The tunnel contracted to the 1.50-inch-diameter circular test section in 6 inches; both the inlet and test sections were polished machined steel, "Pentrated" to prevent rust formation. Four static-pressure taps (1/64-in. holes) were located in the plane of the hot-wire probe. Static taps also extended along the length of the contracted area. As shown in the sketch, the hot-wire probe was mounted in a probe actuator that moved the wire out of the airflow into a small dead-air volume for protection when flow conditions were adjusted. A high-pressure valve packing gland acted as the vacuum seal but allowed the in and out motion of the probe. This simple feature was the primary reason for the long test life of the fine tungsten wire probe (number 109) reported here; the design evolved during the breaking of the first 108 wires.

The tunnel was serviced by the central laboratory air facilities. Test-section static pressure could be varied between 3 and 110 inches of mercury absolute. Mass-flow rate was independently adjustable; in this manner, the corresponding test-section Mach number could be varied between 0 and 0.85. For low mass-flow rates, the air mass flow was metered with a calibrated sonic orifice. The measured tunnel total and static pressures were used to calculate the Mach number assuming isentropic relations for all mass flow above 0.014 pound per second. A water U-tube manometer was used for total-static differences less than 2 inches of mercury; all other pressure readings were read from calibrated mercury manometers. Pressures were measured to at least three significant figures on both water and mercury manometers. Some uncontrollable fluctuations occurred in the inlet air supply, which may have resulted in a random error in reading of the third significant figure.

The total temperature of the air could be varied between -10° and 300° F by alternate use of refrigerator coils and electrical heaters. Total temperature was calculated from the measured recovery temperature of a calibrated thermocouple located in the probe test-section plane (see fig. 2). This temperature was read to the nearest half degree on a self-balancing indicator. Although the tunnel and inlet piping were well insulated, it was difficult to control the air total temperature as closely as desired over all the flow conditions. Deviations from the nominal air temperatures in day-to-day operation were $\pm 10^{\circ}$ F. However, the air temperature listed in table I is probably accurate within $\pm 1^{\circ}$ F of the total air temperature for each data point; uncertainty in total air temperature did not contribute significantly to uncertainty of the calculated Nusselt numbers except for wire temperatures only 50° F above recovery temperature. The effect of air-temperature fluctuations during any tunnel flow setting was minimized by making a linear interpolation between the two temperatures measured at the beginning and end of each set of six wire heat-loss measurements.

Probe design and tungsten wire. - A sketch of the probe used throughout this research is shown in figure 3. Several features of this design bear mentioning. One of the prime requirements is that the wire-supporting prongs do not substantially interfere with the airflow over the wire. Evidence that the design used met the requirement has been supplied by reference 12. Several probes of similar design were used in an experimental determination of the effect of yaw angle of attack on fine-wire heat transfer in reference 12, which concluded that no effect of probe interference could be noted in the results. Another important feature is that the four-wire lead design has matched metal junctions; that is, all unlike metal contacts occur symmetrically. Since the probe body was occasionally in a large temperature gradient (e.g., 300° F at fine-wire supports to 80° F at lead connector), it was important that no unbalanced thermocouple electromotive force exist in

the probe, especially when the wire was operated only 50° F above air temperature. Although some of the early probe designs did not satisfy this requirement, the probe reported here did not show any direct-current unbalance at zero power input for all operating temperatures. Finally, the four-lead-wire design and the use of a Kelvin double bridge minimized the electrical resistance of the probe and its influence on the accuracy of the hot-wire heat-loss measurements. This point is clarified further in the discussion of anemometer electrical equipment.

Tungsten wire with a nominal diameter of 0.0002 inch served as the heat-transfer element of the probe. The mounting technique is described in reference 9. Briefly, the wire is copper-plated at the ends for ease in soldering to the Inconel prongs; a high-temperature soft solder (m.p., 650° F) was used. One of the major drawbacks in the use of fine wires as heat-transfer elements is the uncertainty in the wire diameter (e.g., see ref. 9). In an attempt to decrease this uncertainty, electron micrographs were taken of samples from the spool of wire used on probe 109. These photographs are shown in figure 4; each is a different wire sample. An average diameter was calculated from several diameter measurements near the central position of each photograph. The necked-down section of sample C was not included in this average, which was 0.00022 inch. It can only be hoped that any wire sample as irregular as sample C would be eliminated after its room-temperature resistance was measured. That is, annealed tungsten wires of equal lengths have nearly identical resistance if the wire diameter is uniform. Many probes were discarded as a control procedure when their measured resistance deviated ± 5 percent from the average. Though the average diameter obtained from these samples is not necessarily the diameter of the 0.077-inch-long sample used in probe 109, the average is more probable than the manufacturer's nominal diameter, and 0.00022 inch was used in all calculations.

One of the most important physical properties of tungsten for the calculation of heat loss is the relation between temperature and electrical resistance. Early in the research it was apparent that each wire required calibrating if consistent data of the temperature loading effect on heat-transfer coefficient were to be obtained. Therefore, a small calibration heater was constructed, a sketch of which is given in figure 5. Several wires were silver-soldered to probes so the solder junction was unaffected at 650° F. These wires were then annealed by supplying sufficient current to heat the wire to about twice their room-temperature resistance for 30 minutes. The annealing caused the room-temperature resistance to drop several percent, but after 30 minutes no further change was observed. The probes were then inserted into the heater, and a complete calibration curve was obtained from 32° to 600° F. Two sample curves are given in figure 6(a). In all cases, a 1-milliamperere detection current was used with the Kelvin bridge; therefore, negligible heating above air temperature resulted from the resistance measurement.

A least-square solution for the best parabola through these points gave the coefficients shown in figure 6(a); the curve was represented by $\Omega_w = \Omega_0 [1 + \alpha(T_w - 32) + \beta(T_w - 32)^2]$. From ten such complete resistance-temperature calibration curves, an average value of the second-order coefficient β was calculated to be $3.40 \times 10^{-7} (\text{°F})^{-2}$. Then a partial calibration curve was measured for the soft-soldered wire reported here (probe 109). As shown in figure 6(b), a least-square parabola was determined from the data points assuming $\beta = 3.40 \times 10^{-7} (\text{°F})^{-2}$; the resulting empirical equation was used for all calculations to relate measured wire resistance to wire temperature.

Anemometer electrical equipment. - A sketch of the primary circuit is shown in figure 7. The desired operating wire resistance was set on a Leeds and Northrup Kelvin Double Bridge (Model 4285) to four significant figures. With the switch in "hot" position the constant-average-temperature anemometer circuit varied the power input to the bridge until the wire was heated to the desired resistance and the "error" or galvanometer signal was a minimum. A hand-balanced volt-range potentiometer connected to the potential leads of the double bridge was used to measure the voltage across the hot wire. The power input to the wire element could be reproduced at a given flow setting to at least three significant figures in this manner. To measure the resistance of the unheated wire, the anemometer circuit was switched to "cold" position. This supplied the bridge with about 1-milliampere detection current, and the resistance was found by varying the bridge resistance until a 1.65-microvolt-per-millimeter galvanometer indicated balance.

The use of the Kelvin bridge and four-lead probes made it possible to measure the resistance and voltage drop of only the wire element, solder junction, and support prongs. Since the combined resistance of the junctions and prongs was less than 0.2 ohm, these lead resistances were less than 3 percent of the measured resistances in the worst case.

Procedure

The tunnel was operated at nominal Mach numbers of 0.05, 0.10, 0.20, 0.30, and so on to 0.80. At each Mach number, six static-density settings were used corresponding to nominal wire Knudsen numbers of 0.00916, 0.0143, 0.0256, 0.0416, 0.0555, and 0.0770. Most of these combinations were set at all four nominal total air temperatures of tunnel operation: 0° , 80° , 180° , and 280° F. An important feature of the test procedure was the somewhat random schedule of data taking. The run numbers in tables I and II are chronological. As will be emphasized in the RESULTS section, this procedure decreases the probability of systematic error in the measurements.

After the tunnel had been set at the desired condition and the probe moved into the test section, the manometer readings and test-section total temperature were recorded. The unheated or recovery resistance of the wire was measured next. Then, five or six hot-wire resistances were set and the voltage across the wire was recorded at each setting. About 5 minutes were required for all these heat-loss measurements. Finally, the recovery resistance and manometer-temperature readings were recorded again to complete the procedure.

The measured wire recovery resistance was used as a check of the wire temperature-resistance calibration. At no time during the reported runs did the measured R_e differ from that predicted by figure 6(b), nor the calculated T_e by more than 1 percent and on the average within 0.5 percent; T_e was calculated from the measured air total temperature in a manner discussed in the next section.

DIMENSIONLESS GROUPS OF CORRELATION

In this section, the dimensionless groups used in correlating the data are related to the physical measurements. An energy balance considering convection, conduction, and radiation for a hot wire in steady operation is

$$Q_P = Q_C + Q_K + Q_R \quad (4)$$

The heat input per unit time is simply

$$Q_P = J^2 I^2 R_w \quad (5)$$

The convective heat-loss rate defines the heat-transfer coefficient h :

$$Q_C = h \pi D_w l (T_w - T_e) \quad (6)$$

Equation (6) has equilibrium or recovery temperature T_e of an insulated wire in the temperature difference $(T_w - T_e)$. Therefore, as the wire temperature approaches its recovery value, the convective heat-transfer rate goes to zero. Figure 8 (from ref. 10) is the equilibrium temperature ratio used to obtain T_e from the measured air total temperature. It is well established that, for Knudsen numbers less than 0.10, the equilibrium temperature ratio for normal wires in both slip and continuum flow is a function only of Mach number (refs. 10 and 13 to 16).

The conduction loss rate to the supporting prongs Q_K is discussed in detail in appendix B. The radiation rate Q_R was calculated to be

less than 0.1 percent of the power input Q_p , and no correction for radiation was made. However, since the heat loss to the supports was appreciable, an "end-loss" correction was made.

The Nusselt number is defined as

$$Nu = \frac{hD_w}{k} \quad (7)$$

The air thermal conductivity k has been evaluated at various temperatures by previous investigators. Some use static, others equilibrium or recovery, or total temperature; frequently in engineering work an arithmetic average "film" temperature is used (ref. 11). The guiding principle for empirical data fitting is, of course, to obtain the best correlation. The DISCUSSION section shows that the nonlinear temperature effect on heat-transfer coefficient of both air and wire temperature is too complicated in the slip-flow region for any of these choices to eliminate either "Mach number" or temperature effects. Therefore, for convenience, the air conductivity has been evaluated at total air temperature (k_t). Since the tunnel was operated at set values of total temperature, this choice introduces no Mach number variation into the Nusselt number correlation at constant Knudsen number:

$$Nu_t = \frac{hD_w}{k_t} \quad (7a)$$

The Nusselt number can be expressed in terms of heat loss using equation (6):

$$Nu_t = \frac{Q_C}{\pi l k_t (T_w - T_e)} \quad (8)$$

The convective heat loss Q_C is the difference between the measured power input Q_p and a calculated correction for Q_K . A convenient way to make this correction is to define an uncorrected Nusselt number Nu_t'' , which is completely determined from measured quantities:

$$Nu_t'' \equiv \frac{Q_p}{\pi l k_t (T_w - T_e)} = \frac{J' I^2 \Omega_w}{\pi l k_t (T_w - T_e)} \quad (9)$$

Two published end-loss correction procedures were used, as discussed in appendix B; each gave a correction factor ψ , defined as

$$\psi = \frac{Nu_t}{Nu_t''} \quad (10)$$

Therefore, the tabulated Nusselt numbers were obtained from

$$Nu_t = \psi \frac{J \cdot I^2 \Omega_w}{\pi l k_t (T_w - T_e)} \quad (11)$$

The wire temperature was obtained from measured Ω_w and the resistance-temperature calibration:

$$\Omega_w = \Omega_0 [1 + \alpha(T_w - 32) + \beta(T_w - 32)^2] \quad (12)$$

The equilibrium wire temperature was calculated from figure 8 and the measured total air temperature. The air conductivity k_t was taken from reference 18. All calculations were performed with an IBM 653 digital computer.

The Reynolds number Re_t for the wire was defined by the free-stream (or static) density and velocity; the air viscosity was evaluated at total air temperature (ref. 18):

$$Re_t = \frac{\rho U D_w}{\mu_t} \quad (13)$$

The Knudsen number was calculated from free-stream density and the wire diameter using the formula suggested by reference 14:

$$Kn = \frac{\lambda}{D_w} = \frac{1.5870 \times 10^{-8}}{\rho D_w} \quad (14)$$

The constant 1.5870×10^{-8} has the units pounds(mass) × square feet. Equation (14) assumes that the mean free path for air λ is given by elementary kinetic theory and that $\rho \lambda$ is a constant.

The Mach number was calculated from the velocity measured with a sonic orifice and static temperature:

$$M = \frac{U}{49.02 \sqrt{T}} \quad (15)$$

The measured total-static pressures were used in the isentropic relations ($\gamma = 1.40$) for high-range mass flows to find Mach number.

Finally, the dimensionless turbulent intensity v'/U is known to affect the heat transfer from normal cylinders. However, the excellent work of reference 19 has shown that intensities as high as 20 percent

have negligible effect on heat transfer from fine wires if the scale of turbulence is large compared with cylinder diameter. The intensity of turbulence varied in the test section but was always less than 1 percent. The scale was large compared with D_w . Therefore, turbulence was not a factor in these tests.

RESULTS

Twenty-three plots using all 1100 data points are presented in this section. These figures are intended to show the general consistency and the scope of the data. In the following section, these plots are used to point out some of the complicated effects observed in slip flow. Figure 9 shows the Nusselt number variation with Mach number for specified values of Knudsen number and wire and air temperatures. Figure 9(a) gives results for increasing wire temperatures at a total air temperature of 0° F. Similarly, figures 9(b), (c), and (d) are for air temperatures of 80° , 180° , and 280° F, respectively.

With the exception of the lowest wire temperature at each air temperature, the general consistency of the data is good. There are two experimental checks that can be used as a guide to data reliability. The first has already been discussed in the Procedure section; that is, the recovery resistance of the wire at a given air temperature and Mach number can be checked against the measured air temperature and the resistance-temperature calibration. The fact that these measurements usually checked predicted values within 0.5 percent is evidence that the critical Ω -T calibration did not vary during the course of the experiment. Another check for consistency is reproducibility. To demonstrate this feature, the chronological run numbers are shown with the data points in figure 9(b) for T_w of 583.8° F. The fact that the agreement between check points is good is evidence that the heat-transfer characteristics of the wire were unaffected by dirt accumulation, oxidation, or other uncontrollable factors during the experiment.

The data scatter at the lowest wire temperature for each air temperature is reasonable, because in equation (11) it is clear that constant percentage errors in T_w or T_e are magnified when the difference $(T_w - T_e)$ is small. However, the scatter at $Kn = 0.0770$ and also at $M > 0.50$ is puzzling. No satisfactory explanation for this scatter has been found. The high Knudsen number suggests that the poor correlation may be associated with the rarefied gas flow. For example, reference 20 calculated a "correction" for the temperature-jump phenomenon of slip flow. Accepted slip theory (ref. 21) was used to calculate the temperature jump. Then, by redefining the heat-transfer coefficient in terms of the difference between jump temperature and recovery temperature, a Nusselt number "correction" that depends only Knudsen number was obtained.

The jump phenomenon does not account for the data scatter observed here at low wire temperatures, because the temperature jump is assumed proportional to $(T_w - T_e)$, going to zero as ΔT vanishes. Furthermore, the correction procedure has dubious value when the slip-flow region is approached from free-molecule flow predictions, because the procedure attempts to force data taken in slip flow to fit the form of continuum-flow observations. In this sense, the correction only confuses the over-all correlation and postpones the inevitable deviation from continuum Reynolds number correlations.

DISCUSSION

In this section some of the non-Reynolds-number effects evident in figure 9 are discussed. Then, the dependence of the Nusselt number on both wire and air temperature is considered. These complicated effects fortunately are relatively small compared with the dependence of Nusselt number on the aerodynamic environment. Therefore, the few generalizations that can be inferred from the data concerning these second-order temperature effects are discussed first. Then, a graphical Nusselt number correlation as a function of Reynolds and Knudsen (or Mach) numbers is presented for the slip-flow data of this research. An attempted general Nusselt number correlation for continuum, slip, and free-molecule flows follows, based on these and earlier data together with free-molecule flow theory. Finally, a fluctuation sensitivity equation for hot-wire anemometers is presented that applies to fine wires in subsonic slip flow.

Preliminary Discussion of Results

The following discussion of figure 9 attempts to point out the deviations from simple $\sqrt{Re}$ dependence of continuum flow that are evident in these slip-flow data. Later in this section, the heat-transfer characteristics of cylinders in continuum, slip, and free-molecule flows are considered. The discussion is limited to air at constant temperature where viscosity is constant. If the Nusselt number were a function only of $\sqrt{Re}$, lines of constant $\rho D_w U$ on a logarithmic plot of Nu against U would form a family of parallel straight lines with a common slope of 0.50. The argument changes little if a family of constant Knudsen number lines on a log-log plot of Nusselt number against Mach number is considered. Two important deviations from this behavior should be noted in figure 9. The constant Knudsen number lines are linear only for Mach numbers less than 0.4. The decrease in slope and curvature that occurs around $M = 0.4$ is most pronounced at high Knudsen number where the sensitivity of heat-transfer coefficient to changes in Mach number almost disappears. Secondly, even the straight portions of these

constant Kn curves exhibit slopes other than 0.50. For example, the slopes $(\Delta \log Nu_t)/(\Delta \log M)$ in figure 9(b) for $T_w = 583.8^\circ \text{F}$ from $M = 0.05$ to 0.4 increase with increasing Kn from 0.25 to 0.35.

Therefore, it is clear that no simple power dependence of Nu_t against Re_t should be expected to apply to these data over any appreciable range of variables. Furthermore, the wire and air temperatures can be expected to have only secondary influence on any correlation of the data, because the characteristics just discussed appear in all 23 parts of figure 9.

Effect of Wire Temperature on Heat-Transfer Coefficient

Many cross plots are necessary in order to show clearly what effect varying the wire temperature has on the heat-transfer coefficient at a given flow condition. Figure 10(a), which presents cross plots of figure 9(a), is a plot of Nusselt number as a function of $(T_w - T_e)$ with Knudsen number as a parameter. All plots are for total air temperature of 0°F , and each plot is for a particular Mach number. Similarly, figures 10(b), (c), and (d), which are for total air temperatures of 80° , 180° , and 280°F , respectively, are cross plots of figures 9(b) to (d).

Consider figure 10(b) for $T_t = 80^\circ \text{F}$ and $M = 0.10$. The interesting feature is that the Nusselt number increases for the two lowest values of Knudsen number as the wire temperature is increased. For $Kn = 0.0256$ and 0.0416 , Nu_t does not vary appreciably with ΔT , but at the two highest values of Kn , the heat-transfer coefficient decreases as the wire temperature increases. Furthermore, whether Nu_t increases or decreases, the dependence on wire temperature is greatest for ΔT less than 200°F and tends to vanish for ΔT greater than 200°F . This general picture is repeated for all the subsonic Mach numbers at $T_t = 80^\circ$ (fig. 10(b)). The two anomalous points at $M = 0.05$ are probably experimental errors. The percentage change in Nu_t from $\Delta T = 50^\circ \text{F}$ to the asymptotic value at $\Delta T > 200^\circ \text{F}$ is roughly 20 percent at all Mach numbers for both $Kn = 0.00916$ and $Kn = 0.0770$. There does appear to be a secondary Mach number effect that causes the reversal value of Kn (where the sign of the temperature dependence changes) to increase as M increases. For example, at $M = 0.10$, Nu_t is insensitive to ΔT at $Kn = 0.0256$ and 0.0416 ; but at $M = 0.60$ Nu_t is relatively insensitive to ΔT at higher Kn values (0.0416 and 0.0555).

Therefore, from figure 10(b), the wire temperature appears to affect the heat transfer in a manner primarily dependent on Kn and to a lesser extent on M , over the range of this experiment.

Figures 10(a), (c), and (d) essentially confirm what was observed at $T_t = 80^\circ \text{ F}$ in figure 10(b). The temperature difference $(T_w - T_e)$ again appears to correlate the data into families of curves similar to figure 10(b). It is important to note that between $\Delta T = 50^\circ$ and 200° F at all air temperatures the maximum wire-temperature loading effect is evident, and at $\Delta T > 200^\circ \text{ F}$, Nu_t approaches an asymptote.

Had a nondimensional temperature ratio like $\tau \left(\equiv \frac{T_w - T_e}{T_t} \right)$ been used, this regular feature would not have been observed. In figures 10(c) and (d), the increased air temperature tends to decrease the value of the Knudsen number where the sign of the wire-temperature loading effect reverses. That is, the $Kn = 0.0416$ and 0.0555 lines of both figures 10(c) and (d) show Nu_t increasing with increasing ΔT , while at $T_t = 80^\circ \text{ F}$ these data were either unaffected or decreased as ΔT increased. This same effect of air temperature on the wire-temperature loading may also be seen in figure 10(a) for $T_t = 0^\circ \text{ F}$. Disregarding for the moment the $Kn = 0.00916$ and 0.0143 lines in figure 10(a), it is apparent that the insensitivity to ΔT at $M = 0.40$ to 0.80 persists at lower values of Kn in figure 10(a) than in figure 10(b). No explanation for the apparently anomalous behavior of the $Kn = 0.00916$ and 0.0143 curves in figure 10(a) has been discovered.

However, though the air temperature seems to have a secondary role in the wire-temperature loading phenomenon, it should not confuse the primary observation. That is, for $Kn < 0.02$, the heat-transfer coefficient increases with increasing ΔT up to $\Delta T \approx 200^\circ \text{ F}$, where it assumes an asymptotic value. On the other hand, for $Kn > 0.02$, the heat-transfer coefficient is unaffected or decreases with increasing ΔT to $\Delta T \approx 200^\circ \text{ F}$, where it again assumes an asymptotic value. The Mach number has a secondary role in this wire-temperature loading effect, generally causing the reversal Knudsen number to assume higher values (> 0.02) as the Mach number increases in the subsonic range.

The trends reported here have been noted by previous investigators. The work of reference 16 was mentioned in the INTRODUCTION. The non-linear overheat coefficient ξ defined by equation (3) is given as a function of Reynolds and Mach number by figure 8 of reference 16. For convenience, this figure is included herein as figure 11, and lines of constant Kn are superimposed. Now, it is clear from figure 10 that the heat-transfer coefficient observed in this research is not a linear function of ΔT (or related $\bar{a}_w$ or τ). However, the sign of the overheat coefficient ξ and its dependence on Kn and M is the important feature of figure 11. In general, in subsonic flow for low Kn , figure 11 predicts an increase in Nu_t with ΔT ; a reversal of sign occurs

between $Kn = 0.015$ and 0.020 ; while for Kn greater than these latter values, ξ predicts Nu_t will decrease with increasing ΔT . Furthermore, the Mach number has a secondary role causing the reversal value of Kn to increase. With the exception of the asymptotic behavior at large ΔT observed in this research, the work of reference 16 generally substantiates the results reported here. Since similar effects were noted in reference 14, there can be no doubt that these complicated wire-temperature effects are real, even though of second-order magnitude. Appendix B discusses the sole correction to the primary data (conduction loss) at some length to emphasize the fact that the wire-temperature loading effect cannot be traced to improper handling of the primary data.

Effect of Air Temperature on Heat-Transfer Coefficient

In order to isolate the effect of air temperature on the heat-transfer coefficient, it is of course necessary to eliminate the influence of wire-temperature loading. A logical way to accomplish this distinction would be to extrapolate the Nusselt number curves of figure 10 to $\Delta T = 0$. However, this is the region of maximum curvature, and extrapolation to zero overheat would be very uncertain. The asymptotic value of Nu_t for $\Delta T > 200^\circ \text{F}$ is a more direct Nu_t value that is independent of wire-temperature loading. Therefore, plots of the asymptotic Nu_t ($\Delta T > 200^\circ \text{F}$) are presented in figure 12 as a function of total air temperature at various Mach numbers. Over the entire range of this experiment, the Nu_t decreases with increasing air temperature. The magnitude of this general trend in figure 12 appears to depend primarily on the value of the Nusselt number, being the order of 5 to 10 percent per 100°F for Nu_t between 3.0 and 4.0 but decreasing to 1 to 2 percent per 100°F near $Nu_t = 1.0$. No clear dependence of the air-temperature loading of Nu_t on either Mach or Knudsen number is discernible in this experimental range.

In figure 12, the Nusselt number decreases with increasing temperature, but it is not clear what dependence the heat-transfer coefficient h has on air temperature. Figure 13, which clarifies this point, is a copy of figure 12(b) for $M = 0.50$ with lines of constant heat-transfer coefficient superimposed. If the heat-transfer coefficient were constant and equal to the value observed in 80°F air, then Nu_t would vary with air temperature as shown by the dashed lines in figure 13. That is, the variation in air thermal conductivity k , which causes the T_t dashed-line dependence, is counterbalanced by an increase in heat-transfer coefficient h as the air temperature is increased. However, since h

is not as temperature-dependent as k in this experimental range, the result is a net decrease in Nu_t with rising T_t .

Reference 6 reports good agreement of data taken at $1540^\circ < T_t < 3000^\circ \text{ F}$ with the room-temperature correlation of reference 13. Thus, in the range of this work ($450 < Re < 3000$, $0.3 < M < 0.8$), air temperature had little effect on the Nusselt number, though there is a possibility that the high-temperature correlation is slightly lower than the room-temperature results. Therefore, it appears well established that increasing air temperature causes an increase in heat-transfer coefficient for all subsonic conditions where $Re > 1.0$.

The Prandtl number $c_p \mu / k$ varies from about 0.72 at 0° F to 0.68 at 280° F (ref. 18). Several correlations of Nu_t with Pr were attempted in order to eliminate the air-temperature effect shown in figure 13. However, none of these was successful, although plots of Nu_t / Pr_t^2 or Nu_t / Pr_t^3 did generally reduce the air-temperature dependence. The air-temperature range of this research is too small for any valid conclusions concerning Prandtl number correlations to be inferred.

Correlation of Slip-Flow Heat-Transfer Data

The heat-transfer characteristics of cylinders in slip flow are complicated by second-order dependence on body and air temperature. Nevertheless, a correlation of Nusselt number with the flow parameters is desirable as a first approximation in engineering work even though it does not account for the temperature phenomena. The Preliminary Discussion of Results pointed out what deviations from simple $\sqrt{Re}$ dependence are evident in the data, but figure 9 is not a satisfactory substitute for the conventional correlation of Nu and $\sqrt{Re}$. Figure 14 is an attempt to find a useful correlation. It shows the logarithmic variation of Nu_t with Re_t ; constant M and Kn parametric lines are shown solid and dashed, respectively. Data for $T_t \approx 80^\circ \text{ F}$ and $T_w = 584^\circ \text{ F}$ are plotted in this slip-flow correlation.

The increasing necessity for an additional parameter other than the Reynolds number to correlate these experimental heat-transfer data shows clearly on this plot as Re decreases. This additional parameter is either the Mach number or the Knudsen number. The graphical correlation (fig. 14) makes no distinction between $Nu = f(Re, M)$ or $Nu = f(Re, Kn)$, because both forms are shown. However, only one additional parameter (M or Kn) is independent (eq. (2)). The remainder of this section is devoted to showing that the use of Knudsen number as the additional parameter is preferable. Note that the Kn lines decrease in slope as

Kn increases. However, these constant Kn curves are approaching the slope of the constant Mach number lines at $Kn = 0.00916$. That is, ρD_w is approaching equivalence to U as required for simple Re correlation as Kn decreases; but the decreasing slopes of the Kn curves as $Kn \rightarrow 0.0770$ cause a wide divergence of the constant Mach number lines that is most pronounced at low subsonic M (and low Re).

The preceding discussion of figure 14 emphasizes the fact that the failure of the Reynolds number alone to correlate the data, which has been termed a "Mach number effect" (e.g., p. 34 of ref. 22) and associated with compressibility, is, in fact, a rarefied-gas phenomenon and should be termed a "Knudsen number effect." This distinction is important and not just an arbitrary matter of viewpoint, even though equation (2) may make it so appear. When viewed as a rarefied-gas effect, the large separation of subsonic Mach number lines on a plot of Nu_t against Re_t loses its anomalous features and becomes theoretically predictable. Figure 15 was taken from an approximate slip-flow analysis published in 1953 (ref. 23). The qualitative agreement with the data in figure 14 is excellent, considering the approximations made in the theoretical analysis.

Attempted General Correlation for Nusselt Number in

Continuum, Slip, and Free-Molecule Flows

Figure 16 combines the correlation of the slip-flow data of this research (fig. 14) with the continuum experimental results of reference 13 and the free-molecular-flow theoretical predictions of references 15 and 24. A brief review of these latter reports is followed by a discussion of figure 16 as a whole.

The experimental range of reference 13 is shown in figure 1. The transient response of thermocouples in air was measured, and the results were correlated within 7.4-percent average deviation of a single observation by the following equation:

$$Nu_t = 0.431 \sqrt{Re_t^*} \quad (16)$$

where Re_t^* is a Reynolds number defined by free-stream velocity, total-temperature viscosity, wire diameter, and a density based on static pressure and total temperature. In terms of the Reynolds number defined by equation (13), the Nusselt number correlation of reference 13 is

$$Nu_t = 0.431 \sqrt{Re_t} \left(\frac{T}{T_t} \right)^{1/2} \quad (16a)$$

where

$$\frac{T}{T_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1}$$

The equation applies in range of the experiment: $250 < Re < 30,000$ and $0.1 < M < 0.9$. A partial plot of equation (16a) is shown in figure 17. The important feature is the small effect that changing the subsonic Mach number has on heat transfer at constant Reynolds number. This Mach number effect increases with increasing M and is practically zero below $M = 0.3$. It is reasonable to expect that a compressibility phenomenon would behave in this manner.

An equation for the free-molecular-flow heat transfer from an infinite cylinder in a diatomic gas stream was derived in reference 24. Evaluating all air properties at $80^\circ F$ and assuming an accommodation coefficient of 0.90, this equation may be written as

$$Nu_t = 0.0297 \frac{g(s)}{Kn} \left(\frac{T}{T_t}\right)^{1/2} \quad (17)$$

where $g(s)$ is a defined function of Mach number plotted in figure 18. Equation (17) applies to all $Kn > 2$. Figure 19 is a plot of equation (17) for $Kn > 2$; it also gives the predictions of slip theory for $Kn < 2$. Although several of the essential features of this free-molecule analysis have been confirmed experimentally, equation (17) has not been tested over an appreciable range of variables. However, free-molecule-analysis theoretical predictions are generally believed reliable. The two essential features of figure 19 for $Kn > 2$ are the first-power dependence on Re and the large separation of subsonic M lines.

Returning to figure 16, the slip-flow experimental data extrapolate smoothly into the continuum-flow empirical curve. However, the slip-flow correlation at $Kn = 0.0770$ cannot be extrapolated to the free-molecule-flow correlation at $Kn = 2$. Nevertheless, several of the trends required by the rarefied-gas analysis are evident in the data. The slip-flow data constant M lines increase in slope and may be approaching first-power Re_t dependence at $Kn = 0.0770$. Furthermore, the increasing Kn dependence causes a spread of the constant M lines at $Kn = 0.0770$ that is most pronounced at low subsonic M . Before the attempted correlation in figure 16 can be reliably extended below $Re = 1.0$, it will be necessary to obtain experimental data between Kn of 0.10 and 10.0. Until these data are published, the theoretical curves from the approximate slip-flow analysis of reference 23 between Kn of 0.04 and 2 shown in figure 19 may be used as a first approximation together with the free-molecule-flow prediction for $Kn > 2$.

Finally, the suggested curve of reference 11 is shown in figure 16 for easy comparison. The low Reynolds number data used to obtain this curve were for very low velocities ($Kn < 0.01$). Furthermore, the attempted general correlation and the reference 11 correlation are not comparable, strictly speaking, because total air temperature was used for calculating conductivity and viscosity in the proposed correlation, while an average "film" temperature was used in reference 11.

Hot-Wire-Anemometer Sensitivity

One application of the heat-transfer correlations presented in the preceding section is for hot-wire-anemometer sensitivity. King's equation (1) sensitivity for wire $Re < 250$ is a crude approximation because the Knudsen number effect complicates the Reynolds number correlation. In the following paragraphs, a sensitivity equation based on dimensionless group correlations is proposed. However, as in the past, the only reliable hot-wire sensitivity is a direct calibration of the particular wire over the flow range of operation. The sensitivity equation serves as a guide to performing this calibration.

The Nusselt number correlation given in figure 14 may be expressed in a general manner as

$$Nu_t = f(M, Kn, \Delta T, T_t) \quad (18)$$

The dependence on ΔT and T_t causes up to 20-percent deviations from figure 14 in a complicated manner. The following derivation assumes that the anemometer wire operates at constant temperature (e.g., see ref. 9). This eliminates the functional dependence of Nu_t on ΔT . It is convenient to express the remaining T_t dependence in equation (18) with a dimensionless temperature ratio τ :

$$\tau = \frac{T_w - \eta T_t}{T_t} = \frac{\Delta T}{T_t} \quad (19)$$

The recovery temperature ratio η (fig. 8) will be assumed a function only of Mach number; this is true for $Kn < 0.10$.

The general sensitivity for a constant-temperature anemometer wire to fluctuating flow velocity, density, and total temperature may be written as

$$2I\Omega_w dI = \frac{\partial}{\partial U} \left[\frac{\pi}{J} k_t Nu_t (T_w - \eta T_t) \right] dU + \frac{\partial}{\partial \rho} \left[\frac{\pi}{J} k_t Nu_t (T_w - \eta T_t) \right] d\rho + \frac{\partial}{\partial T_t} \left[\frac{\pi}{J} k_t Nu_t (T_w - \eta T_t) \right] dT_t \quad (20)$$

Recalling that it is assumed that the wire temperature is maintained constant by a fluctuating feedback current, denoted by i ($=dI$), then equation (20) becomes

$$i = \frac{I}{200} \left[- \left(1 + \frac{\gamma - 1}{2} M^2 \right) \frac{M}{\tau} \frac{\partial \eta}{\partial M} - \frac{\eta}{\tau} (\gamma - 1) M^2 + \left(1 + \frac{\gamma - 1}{2} M^2 \right) \frac{\partial \log Nu}{\partial \log M} \right] \\ \times \frac{100 \delta U}{U} + \frac{I}{200} \left(- \frac{\partial \log Nu}{\partial \log Kn} \right) \frac{100 \delta \rho}{\rho} + \frac{I}{200} \left(\frac{\partial \log k}{\partial \log T_t} - \frac{\eta}{\tau} - \frac{\tau + \eta}{Nu} \frac{\partial Nu}{\partial \tau} \right) \frac{100 \delta T}{T_t} \quad (21)$$

Appendix C gives the derivation of equation (21), which relates the fluctuating current i of a constant-temperature anemometer wire to the fluctuating flow variables velocity fluctuation δU , density fluctuation $\delta \rho$, and total-air-temperature fluctuation δT . The average wire current I refers to an infinitely long wire if the sensitivity slopes are taken from Nu_t rather than Nu_t'' plots. The second-order dependence of the general correlation (fig. 14) on air and wire temperatures complicates generalizations concerning the major sensitivity slopes:

$\frac{\partial \log Nu}{\partial \log M}$, $\frac{\partial \log Nu}{\partial \log Kn}$, and $\frac{\partial Nu}{\partial \tau}$. However, since over a small range of variables each of the logarithmic slopes is linear and approximately independent of the magnitude of the independent variable, it is possible to make two limited generalizations. Figure 20 gives the measured slopes from figure 9(b) for T_w of 583.8° F and its cross plot; these terms are applicable at $T_t \approx 80^\circ$ F and $\Delta T > 200^\circ$ F.

The utility of equation (21) is limited by the lack of a precise universal correlation. However, if the turbulent velocity intensity is the quantity of interest in airflows of $M < 0.4$, equation (21) simplifies considerably. Under these circumstances, density fluctuations are frequently negligible; and, unless heat is added to or taken from the airstream, the total-air-temperature fluctuations are also negligible. The predominant term in the velocity sensitivity is $(\partial \log Nu)/(\partial \log M)$, and this term is as easily obtained experimentally as the usual King's equation calibration curve, perhaps requiring only a larger range of velocity variation.

Finally, it should be pointed out that reference 22 presents sensitivity equations similar to equation (21) for constant-current anemometry, with special emphasis on supersonic-flow applications. In subsonic and transonic applications, equation (21) has the advantage that the Reynolds number was not chosen as an independent variable (M and Kn , rather than M and Re). The use of Reynolds number introduces additional terms in the velocity sensitivity.

CONCLUDING REMARKS

The following conclusions can be drawn from the heat-transfer measurements for cylinders in slip flow presented in this report:

1. An attempted Nusselt number correlation for heat transfer from normal cylinders in subsonic continuum, slip, and free-molecule air-flows is given as figure 16. Slip-flow experimental data of this paper extrapolate into existing continuum-flow experimental data for low values of Knudsen number ($Kn < 0.01$). The slip-flow data qualitatively verify trends predicted by free-molecule-flow theory ($Kn > 2$) at Kn approaching 0.10; but extrapolation does not give quantitative agreement. Further experiments in the transition region between slip and free-molecule flows are necessary to complete the general correlation.

2. Empirical equations that give the Nusselt number as a constant power of Reynolds number, familiar in continuum flow, are progressively in error for $Re < 250$ because of increasing Kn dependence in the slip-flow region. The correlation of Nusselt number for this slip-flow experiment is shown graphically in figure 14 as a function of Reynolds and Knudsen or Mach numbers. This dependence is too complicated for an empirical equation with engineering utility, although simple equations have previously been proposed in both continuum and free-molecule flows.

3. The approximate slip-flow analysis of reference 23 correctly predicts the trends observed but fails to fit the data quantitatively.

4. For air temperatures between 80° and 280° F, the heat-transfer coefficient h increases with increasing temperature difference ΔT at low Kn (< 0.02). This nonlinearity in h with ΔT has commonly been observed in continuum-flow experiments. However, with air temperatures between 0° and 280° F, at high Kn (> 0.02) the heat-transfer coefficient decreases with increasing ΔT . In both cases, the effect of ΔT was greatest for ΔT below 200° F, tending to disappear at ΔT greater than 200° F. A secondary Mach number effect causes the reversal Knudsen number of about 0.02 to shift to larger values as M increases. The major trends are corroborated by the work of reference 16.

5. For wires operated at ΔT greater than 200° F, an increase of air temperature causes the heat-transfer coefficient h to increase. This occurs for all flow conditions of this research. The increase in air thermal conductivity with total air temperature tends to cancel the variation of Nusselt number $Nu_t (= hD_w/k_t)$ with air temperature. However, Nu_t decreases slightly with increasing air temperature because the thermal conductivity has a greater temperature-dependence than the heat-transfer coefficient in the range of this research.

6. Constant-temperature hot-wire-anemometer sensitivity to velocity, density, and total-air-temperature fluctuations is extremely complicated with the probe in subsonic slip flow. General sensitivity equations together with a few generalizations observed in this research have been presented. However, individual calibration of wires in the flow range of interest is the only reliable technique for subsonic applications because (a) King's law is a very special case of hot-wire sensitivity ($Kn < 0.001$, $M < 0.3$), and (b) complicated nonlinearity of heat transfer with wire and air temperature prevents accurate generalizations using dimensionless groups.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 28, 1958

APPENDIX A

SYMBOLS

A	King's equation intercept (eq. (1)), $A = a/k$
A'	dimensionless King's equation intercept (eq. (1a)), $A' = a/\pi\Omega_0\alpha$
A_w	cross-sectional area of wire, sq ft
a, b	dimensionless empirical constants (eq. (1))
a^*	dimensionless term in eq. (B24)
a_s	speed of sound
$\bar{a}_w$	resistance ratio, $(\Omega_w - \Omega_e)/\Omega_e$
B	King's equation slope (eq. (1)), $B = b/\sqrt{D_w\rho c_p k}$
B_1, B_2	empirical constants (eq. (B16))
B'	dimensionless King's equation slope (eq. (1a)), $B' = b/\pi\Omega_0\alpha$
B^*	dimensionless term defined by eq. (B18)
C	ratio of heat lost by conduction to supports to heat lost to air by convection (eq. (B13))
c_p	isobaric specific heat
D_s	support diameter, ft or in.
D_w	wire diameter, ft or in.
e, G	dimensionless terms defined by eq. (B20)
g_c	conversion factor to engineering units, $(\text{lb(M)})(\text{ft})/\text{lb(F)}\text{-sec}^2$
h	convective heat-transfer coefficient (eq. (6))
h_0	heat-transfer coefficient extrapolated to $\Delta T = 0$
I	wire current, amp
J	conversion of Btu to ft-lb(F)

J'	conversion of watts to Btu/sec, 9.484×10^{-4}
K_S	thermal conductivity of Inconel support, Btu/(sec)(ft)(°F)
K_W	thermal conductivity of tungsten wire, Btu/(sec)(ft)(°F)
Kn	Knudsen number, λ/D_W
k	thermal conductivity of air, Btu/(sec)(ft)(°F)
l	length of wire, ft
M	Mach number
Nu	Nusselt number, hD_W/k
Nu''	Nusselt number uncorrected for heat loss to supports (eq. (9))
Pr	Prandtl number, $c_p\mu/k$
Q	length-average heating rate, Btu/sec
q	heating rate per unit length, Btu/(ft)(sec)
Re	Reynolds number, $\rho D_W U/\mu$
$Re_{f,s}$	Reynolds number of support, $\rho U D_S/\mu_{f,s}$
S	dimensionless term defined by eq. (B25)
T	static or free-stream air temperature
ΔT	temperature difference, $T_W - T_e$
T_a	air temperature
T_e	recovery or equilibrium wire temperature
T_t	total air temperature
T_W	length-average wire temperature
$T_{W,\infty}$	length-average temperature of infinitely long wire, $T_{W,\infty} \equiv \sigma_1/\sigma$
t^*	dimensionless ratio (eq. (B18))
t_w	local wire temperature at any point x

U	free-stream air velocity, ft/sec
v'	rms turbulent velocity, ft/sec
x	any position along length of wire, $x = 0$ at wire center
Y	dimensionless term defined by eq. (B18)
z	factor in end-loss correction procedure, defined by eq. (B19)
α	first-order coefficient of electrical resistance - temperature relation (eq. (12)), $^{\circ}\text{F}^{-1}$
β	second-order coefficient of electrical resistance - temperature relation (eq. (12)), $^{\circ}\text{F}^{-2}$
γ	ratio of specific heats, 1.4 for air
δ	perturbation component
η	recovery temperature ratio, $\eta \equiv T_e/T_t$
λ	mean free path of air, ft
μ	air viscosity, $\text{lb(M)}/(\text{ft})(\text{sec})$
ξ	nonlinear overheat coefficient (eq. (3))
ρ	air density, $\text{lb(M)}/\text{cu ft}$
σ	coefficient defined in eq. (B7)
σ_1	coefficient defined in eq. (B8)
τ	temperature ratio, $\tau \equiv (T_w - T_e)/T_t$
ψ	end-loss correction ratio, $\psi \equiv \text{Nu}/\text{Nu}''$
Ω_a	length-average wire resistance at air temperature T_a , ohms
Ω_e	length-average wire resistance at recovery air temperature T_e , ohms
Ω_w	length-average wire resistance at hot-wire temperature T_w , ohms
Ω_0	length-average wire resistance at 32°F , ohms
ω	wire resistance per unit length, ohms/ft

Subscripts:

C	convection
f	film temperature, $T_f \equiv (T_s + T_e)/2$
K	conduction
m	measured
P	production
R	radiation
s	support (except a_s)
t	total air temperature T_t
w	wire or cylinder
O	evaluated at 32°F (except h_0)

APPENDIX B

CORRECTIONS FOR CONDUCTION TO SUPPORTS

Linear Correction

The steady-state heat transfer from a hot wire having negligible radiant heat loss is treated by Lowell in reference 10, where equations for making precise corrections for finite wire length are presented. Except for a minor innovation, the following analysis is that of reference 10.

The energy-balance equation at any cross section x for this problem is simply

$$q_P = q_C + q_K \quad (B1)$$

The convection heat loss per unit length of wire at x can be expressed as

$$q_C = hD_w \pi (t_w - T_e) = \pi k_t Nu_t (t_w - T_e) \quad (B2)$$

The expression for conduction of heat to the supports can be simplified if it is assumed that the heat flow through the wire is one-dimensional and that the wire thermal conductivity K_w is not affected by temperature:

$$q_K = - K_w A_w \frac{d^2 t_w}{dx^2} \quad (B3)$$

Neglecting the second-order term $\beta(t_w - 32)^2$, the resistance per unit length of wire can be written in terms of the local wire temperature:

$$\omega = \omega_0 [1 + \alpha(t_w - 32)] \quad (B4)$$

where ω_0 is the resistance per unit length in ohms per inch at 32° F. Substituting equations (B2) to (B4) into (B1),

$$J^2 I^2 \omega_0 [1 + \alpha(t_w - 32)] = \pi k_t Nu_t (t_w - T_e) - K_w A_w \frac{d^2 t_w}{dx^2} \quad (B5)$$

Equation (B5) can be written more simply as

$$\frac{d^2 t_w}{dx^2} - \sigma t_w = -\sigma_1 \quad (B6)$$

where the constants are defined as follows:

$$\sigma \equiv \frac{\pi k_t Nu_t - J' I^2 \omega_0 \alpha}{K_w A_w} \quad (B7)$$

$$\sigma_1 \equiv \frac{\pi k_t Nu_t T_e + J' I^2 \omega_0 \alpha \left(\frac{1}{\alpha} - 32 \right)}{K_w A_w} \quad (B8)$$

The lengthwise variation of $k_t Nu_t$ or its equivalent hD_w is ignored; that is, h is assumed unaffected by t_w or T_e .

Equation (B6) is a second-order, ordinary differential equation with constant coefficients. The following boundary conditions are used to find the temperature distribution along the wire length:

(1) The wire is symmetrical; therefore, at the center of the wire (at $x = 0$), the temperature gradient must be zero: $\left. \frac{dt_w}{dx} \right|_{x=0} = 0$.

(2) The temperature at each support, $x = \pm l/2$, is $T_{w,s}$ (an as yet undetermined temperature, but physically it is known that $T_e \geq T_{w,s} \geq T_w$).

The solution of equation (B6) satisfying these conditions is

$$t_w = T_{w,\infty} - (T_{w,\infty} - T_{w,s}) \frac{\cosh \frac{\sigma^{1/2} x}{2}}{\cosh \frac{\sigma^{1/2} l}{2}} \quad (B9)$$

The measured mean resistance Ω_w is related to the length-average wire temperature ($\omega_0 l = \Omega_0$):

$$\Omega_w = \Omega_0 [1 + \alpha(T_w - 32)] \quad (B10)$$

Here, T_w is obtained from integration of (B9) over the wire length:

$$T_w = T_{w,\infty} - \frac{T_{w,\infty} - T_{w,s}}{\frac{\sigma^{1/2} l}{2}} \tanh \frac{\sigma^{1/2} l}{2} \quad (B11)$$

Having obtained the wire-temperature distribution, the next step is to write an energy balance on the entire wire. The power input is now written in terms of equation (B10), the convection loss in terms of (B11), and the conduction loss in terms of the derivative of (B9) evaluated at the point of attachment ($x = l/2$):

$$\begin{aligned} J^2 I^2 \omega_0 [1 + \alpha(T_w - 32)] \\ = \pi k_t \text{Nu}_t (T_w - T_e) + \frac{2K_w A_w \sigma^{1/2}}{l} (T_{w,\infty} - T_{w,s}) \tanh \frac{\sigma^{1/2} l}{2} \end{aligned} \quad (B12)$$

At this point, it is convenient to define a quantity C as the ratio of the heat lost by conduction to the supports to that lost directly to the airstream by convection:

$$C \equiv \frac{4K_w A_w}{l^2} \frac{(T_{w,\infty} - T_{w,s}) \left(\frac{\sigma^{1/2} l}{2} \right) \tanh \frac{\sigma^{1/2} l}{2}}{\pi k_t \text{Nu}_t (T_w - T_e)} \quad (B13)$$

Equation (B12) can be expressed in terms of C as follows:

$$J^2 I^2 \omega_0 [1 + \alpha(T_w - 32)] = \pi k_t \text{Nu}_t (T_w - T_e) (1 + C) \quad (B14)$$

The only unknown in C (other than Nu_t) is the temperature at the support $T_{w,s}$. An energy balance on the support is made to determine $T_{w,s}$. The problem is analogous to the wire treatment just outlined except that the heat input is the conduction from the wire, the output is convection from the support, and the electrical power input is assumed zero in the supports. Solving this energy balance for $T_{w,s}$ and approximating $\tanh(\sigma^{1/2} l/2)$ as 1.0 give the following:

$$T_{w,s} = \frac{2\text{Nu}_{f,s}^{1/2} k_f^{1/2} K_s^{1/2} D_s T_e + K_w D_w^2 \sigma^{1/2} T_{w,\infty}}{2\text{Nu}_{f,s}^{1/2} k_f^{1/2} K_s^{1/2} D_s + K_w D_w^2 \sigma^{1/2}} \quad (B15)$$

Since the objective of the foregoing analysis of the heat transfer from the support was to determine $T_{w,s}$ in terms of known quantities (so that ultimately the end loss ratio C could be found), it appears that the introduction of $Nu_{f,s}$ in equation (B15) has simply replaced one unknown by another. Fortunately, the Nusselt number of the support can be adequately represented by the following empirical relation, because the support is large and in continuum flow:

$$Nu_{f,s} = B_1 + B_2(Re_{f,s})^n \quad (B16)$$

where

$$Re_{f,s} = \frac{\rho U D_s}{\mu_{f,s}}$$

Equation (B16) neglects the small Mach number effect observed at $Re > 250$. Following are values of n , B_1 , and B_2 from reference 11 (p. 260, table 10-4):

$Re_{f,s}$ range	n	B_1	B_2
0.1 - 1000	0.52	0.32	0.43
1000 - 50,000	.60	0	.24

Equations (B13), (B15), and (B16) can be combined with equation (B14); the only unknown quantity is the corrected wire Nusselt number Nu_t . Lowell (ref. 10) has shown that the combination of essentially the equations just mentioned can be written as

$$C = \frac{1 - t^*(1 + C)}{B^*[(1 + C)^{-1} - t^*] + Y[(1 + C)^{-1} - t^*]^{1/2} - 1} \quad (B17)$$

where

$$\left. \begin{aligned} t^* &\equiv \frac{T_w - T_e}{\left(\frac{1}{\alpha} - 32\right) + T_w} \\ B^* &\equiv \frac{2k_t Nu_t''}{(B_1 + B_2 Re_{f,s}^n)^{1/2} K_s^{1/2} k_{f,s}^{1/2} D_s} \\ Y &\equiv \left(\frac{k_t}{K_w}\right)^{1/2} \frac{l}{D_w} (Nu_t'')^{1/2} \end{aligned} \right\} \quad (B18)$$

A more usable form of equation (B17) was derived by Lowell after reference 10 was published. Another form of the ratio of corrected to uncorrected Nusselt number was defined as follows:

$$\frac{Nu_f}{Nu_f^*} = \frac{1}{1 + C} \equiv (1 - t^*) \left(\frac{t^*}{1 - t^*} + z^2 \right) \quad (B19)$$

Then, by letting

$$\left. \begin{aligned} e &\equiv Y(1 - t^*)^{1/2} \\ G &\equiv B^*(1 - t^*) \end{aligned} \right\} \quad (B20)$$

an algebraically simpler expression for equation (B19) is obtained:

$$Gz + e = \frac{1}{z - z^3} \quad (B21)$$

The procedure used to calculate Nu_t for table I was to solve (B21) for the root of z between $z = 0.5$ and $z = 1.0$. This solution is straightforward once the physical constants in both G and e are evaluated. The following values were used in the electronic digital computer data-reduction program:

Tungsten wire: $l = 0.077$ in.

$$D_w = 2.2 \times 10^{-4} \text{ in.}$$

$$\alpha = 2.24 \times 10^{-3} \text{ } ^\circ\text{F}^{-1}$$

$$K_w = 3.43 \times 10^{-2} \text{ Btu}/(\text{sec})(\text{ft})(^\circ\text{F})$$

Inconel support: $D_s = 0.027$ in. (at point of attachment)

$$K_s = 2.19 \times 10^{-3} \text{ Btu}/(\text{sec})(\text{ft})(^\circ\text{F})$$

Air properties: $\left. \begin{aligned} \mu_{f,s} &\approx \mu_t \\ k_{f,s} &\approx k_t \end{aligned} \right\} (\text{ref. 18})$

Another method of making end-loss corrections on hot-wire data has been widely used by investigators at other laboratories. Essentially, it is a limiting case of the more general method just outlined. Kováshay originally published the method (without derivation) in reference 7; reference 25 gives a more complete presentation.

The problem is identical to that treated by Lowell, except that Kovasznay uses the mathematically simpler boundary condition $T_{w,s} = T_e$. Since the recovery temperature T_e is immediately available, equations (B7) and (B12) can be solved without further ado for Nu_t . A further simplification can be gained if the reference temperature of the calibration of wire temperature and resistance is taken at T_e rather than at 32° F as in the previous section. If these substitutions are made in equations (B13) and (B14), it can be shown that the following equation is the desired solution for ψ :

$$\frac{Nu_t}{Nu_t''} = \frac{\frac{\bar{a}_w}{a_*} + \bar{a}_w}{1 + \bar{a}_w} \quad (B22)$$

where

$$\bar{a}_w = \frac{\Omega_w - \Omega_e}{\Omega_e} \quad (B23)$$

$$\frac{\bar{a}_w}{a_*} = 1 - S \left(\frac{a_*}{\bar{a}_w} \right)^{1/2} \tanh \frac{1}{S} \left(\frac{\bar{a}_w}{a_*} \right)^{1/2} \quad (B24)$$

$$S = \frac{D_w (K_w)^{1/2}}{l (k_t)} Nu_t''^{-1/2} (1 + \bar{a}_w)^{1/2} \quad (B25)$$

This procedure was also used in the data-reduction program. The results of this end-loss correction agreed with those obtained using equation (B21) within a small fraction of 1 percent of Nu_t for all flow conditions of this research. Therefore, the probe supports did act effectively as an infinite sink. That is, the wire-support junction was effectively maintained at recovery temperature, $T_e \approx T_{w,s}$.

Nonlinear Correction

The linear correction procedures just outlined are rather elaborate. However, the methods differ only in the manner used to treat the temperature of the wire-support junction. Both procedures assume that the wire has no second-order temperature dependence ($\beta = 0$), that the heat-transfer coefficient is not dependent on wire temperature, and that the wire thermal conductivity is constant. Generally, none of these

assumptions are true. So, it is conceivable that the end-loss correction is incorrect and that this mistake causes the nonlinearity of Nu_t with ΔT and T_t . An excellent discussion of this problem is published in reference 16. Mechanically integrated solutions of the nonlinear equation that includes β , ξ (eq. (3)), and $K_w = f(t_w)$ are compared with the linear solution, and it is concluded that the linear solution of Kováshay differs by only 1/2 percent from the nonlinear solutions for any realistic probe design. Therefore, the procedure used to correct for finite wire length in this report is adequate.

APPENDIX C

DERIVATION OF HOT-WIRE-ANEMOMETER SENSITIVITY EQUATIONS

Assume that the general heat-loss characteristics of normal cylinders are known in terms of Nusselt number corrected for conduction loss to supports. Specifically, the Nusselt number is a function of the Mach and Knudsen (or Reynolds) numbers, and the effect of air temperature at constant wire temperature is assumed described by a single parameter τ :

$$Nu_t = f(M, Kn, \tau) \quad (C1)$$

$$\tau = \frac{T_w - T_e}{T_t} \quad (C2)$$

The subscript t on Nu and k will be dropped here and understood throughout appendix C. The recovery temperature ratio η will be assumed to be independent of Kn , as in figure 8; this is valid at least to $Kn = 0.10$:

$$\eta = \frac{T_e}{T_t} = f(M) \quad (C3)$$

The heat loss from a wire may be written as

$$J^2 I^2 \Omega_w = \pi l k (T_w - \eta T_t) Nu \quad (C4)$$

Equation (C4) assumes that Nu is corrected for finite wire length so that I^2 is the square of the measured wire current times the end-loss correction factor, ψI_m^2 . Naturally, if a calibration curve for a particular wire is being used, it is possible to set $\psi = 1$ and correlate data as Nu'' .

It will be assumed that the hot-wire resistance (and temperature) is maintained constant by a fluctuating feedback current:

$$2J^2 I \Omega_w dI = \frac{\partial}{\partial U} [\pi l k (T_w - \eta T_t) Nu] dU + \frac{\partial}{\partial \rho} [\pi l k (T_w - \eta T_t) Nu] d\rho + \frac{\partial}{\partial T_t} [2l k (T_w - \eta T_t) Nu] dT_t \quad (C5)$$

If the fluctuating current dI is set equal to i and small finite flow fluctuations are approximated by δ to replace the derivatives, equation (C5) can be written as

$$\begin{aligned}
 i = & \left[\frac{\pi l}{2J'I\Omega_w} kNuT_t \left(-\frac{\partial \eta}{\partial U} \right) + \frac{\pi l}{2J'I\Omega_w} kNu\eta \left(-\frac{\partial T_t}{\partial U} \right) + \frac{\pi l}{2J'I\Omega_w} k(T_w - \eta T_t) \frac{\partial Nu}{\partial U} \right] \delta U \\
 & + \left[\frac{\pi l}{2J'I\Omega_w} k(T_w - \eta T_t) \frac{\partial Nu}{\partial \rho} \right] \delta \rho \\
 & + \left[\frac{\pi l}{2J'I\Omega_w} (T_w - \eta T_t) Nu \frac{\partial k}{\partial T_t} - \frac{\pi l}{2J'I\Omega_w} kNu\eta + \frac{\pi l}{2J'I\Omega_w} k(T_w - \eta T_t) \frac{\partial Nu}{\partial T_t} \right] \delta T_t
 \end{aligned} \tag{C6}$$

It will be convenient to introduce the following dimensionless groups to generalize equation (C6) for numerical evaluation of the various sensitivity derivatives:

$$\frac{\partial}{\partial \rho} = \frac{\partial Kn}{\partial \rho} \frac{\partial}{\partial Kn} = -\frac{Kn}{\rho} \frac{\partial}{\partial Kn} \tag{C7}$$

$$\frac{\partial}{\partial U} = \frac{\partial M}{\partial U} \frac{\partial}{\partial M} = \frac{1 + \frac{\gamma - 1}{2} M^2}{a_s} \frac{\partial}{\partial M} \tag{C8}$$

$$\frac{\partial T_t}{\partial U} = \frac{U}{c_p g_c J} \tag{C9}$$

$$\frac{\partial}{\partial T_t} = \frac{\partial \tau}{\partial T_t} \frac{\partial}{\partial \tau} = -\frac{\tau + \eta}{T_t} \frac{\partial}{\partial \tau} \tag{C10}$$

Substituting (C7) to (C10) into equation (C6) and recalling that

$$M = \frac{U}{a_s} \quad \text{and} \quad \frac{I}{2Nu} = \frac{\pi l}{2J'I\Omega_w} k(T_w - \eta T_t), \quad \text{the following form may be written:}$$

$$\begin{aligned}
 i = & \frac{I}{2} \left[-\left(1 + \frac{\gamma - 1}{2} M^2\right) \frac{M}{\tau} \frac{\partial \eta}{\partial M} - \frac{\eta}{T_w - \eta T_t} \frac{U^2}{c_p g_c J} + \left(1 + \frac{\gamma - 1}{2} M^2\right) \frac{M}{Nu} \frac{\partial Nu}{\partial M} \right] \frac{\delta U}{U} \\
 & + \frac{I}{2} \left[-\frac{Kn}{Nu} \frac{\partial Nu}{\partial Kn} \frac{\partial \rho}{\rho} + \frac{I}{2} \left(\frac{T_t}{k} \frac{\partial k}{\partial T_t} - \frac{\eta T_t}{T_w - \eta T_t} - \frac{\tau + \eta}{Nu} \frac{\partial Nu}{\partial \tau} \right) \frac{\delta T_t}{T_t} \right]
 \end{aligned} \tag{C11}$$

Replacing $\left(\frac{u}{v} \frac{\partial v}{\partial u}\right)$ by $\frac{\partial \log v}{\partial \log u}$ and using a familiar identity, the sensitivity equation can be written in its final form, which is given as equation (21) of the text.

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TABLE I. - RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ^a	Nu _t	Run ^a	M	Kn	Re _t	T _t	T _w	Nu _t ^a	Nu _t	Run			
0.0488	0.0753	0.9763	12.9	33.6	1.054	0.7396	342	0.0503	0.0255	2.867	87.5	133.2	1.303	0.9931	133			
		.9814	11.5	86.6	.9479	.6534	343						183.6	1.325	1.022	134		
		.9874	9.9	183.6	.9212	.6402	344						283.2	1.299	1.013	135		
0.0490	0.0143	4.677	272.9	333.2	1.361	1.089	319	0.0506	0.0442	1.662	85.0	133.2	1.081	0.7928	109			
		4.679	272.7	383.9	1.402	1.133	320						183.6	1.086	.8050	110		
		4.685	272.1	483.4	1.429	1.170	321						283.2	1.066	.7994	111		
		4.689	271.8	583.8	1.450	1.199	322						383.9	1.051	.7947	112		
		4.693	271.4	620.0	1.456	1.208	323						483.4	1.037	.7891	113		
	0.0748	0.9973	8.5	33.6	1.058	0.7428	420						583.8	1.031	.7883	114		
		.9952	9.0	86.6	.9783	.6803	421	0.0507	0.0253	2.762	196.6	233.1	1.281	0.9981	223			
		.9930	9.6	183.6	.9360	.6538	422						2770	195.5	283.2	1.244	.9717	224
		.9909	10.2	383.9	.9031	.6301	423						2.779	194.4	383.9	1.236	.9768	225
		.9888	10.7	483.4	.8897	.5961	424						2.787	193.2	483.4	1.235	.9858	226
		.9866	11.3	583.8	.8802	.5915	425						2.795	192.1	583.8	1.237	.9967	227
0.0492	0.0142	5.239	8.4	33.6	2.002	1.596	348	0.0508	0.0403	1.711	265.5	333.2	0.9844	0.7457	288			
		5.222	9.3	86.6	1.797	1.424	349						1.716	264.2	383.9	.9849	.7514	289
		5.206	10.1	183.6	1.715	1.370	350						1.721	262.9	483.4	.9922	.7671	290
		5.190	10.9	383.9	1.698	1.384	351						1.726	261.7	583.8	.9945	.7769	291
		5.174	11.7	483.4	1.696	1.394	352						1.732	260.4	620.0	.9988	.7830	292
	0.0551	1.308	71.5	133.2	1.021	0.7364	85	0.0513	0.0575	1.202	274.3	333.2	0.8621	0.6358	283			
		183.6	1.003	.7278	86	1.206	272.9						383.9	.8667	.6447	284		
		283.2	.9908	.7280	87	1.209	271.8						483.4	.8680	.6540	285		
		383.9	.9819	.7281	88	1.213	270.1						583.8	.8678	.6606	286		
		483.4	.9619	.7147	89	1.216	269.2						620.0	.8656	.6606	287		
		0.0495	0.0744	0.9724	72.5	132.0	0.9212	0.6468	1	0.0782	0.8818	283.1	333.2	0.7475	0.5332	278		
				183.0	.9094	.6426	2	.8855	281.3					383.9	.7538	.5431	279	
234.5	.9082			.6471	3	.8893	279.5	483.4	.7603					.5562	280			
285.1	.9008			.6450	4	.8931	277.6	583.8	.7589					.5608	281			
332.6	.8960			.6441	5	.8969	275.8	620.0	.7557					.5595	282			
386.5	.8871			.6390	6	0.0516	0.0582	1.234	187.2					233.1	0.8849	0.6398	193	
437.3	.8815	.6359	7	1.233	187.6					283.2	.9112	.6692	194					
488.0	.8712	.6273	8	1.232	188.0					383.9	.9110	.6789	195					
538.5	.8638	.6201	9	1.231	188.3					483.4	.9036	.6799	196					
590.2	.8572	.6120	10	1.229	188.7					583.8	.8987	.6815	197					
640.4	.8439	.5926	11	1.228	189.0					620.1	.8965	.6814	198					
0.0496	0.0570	1.331	3.5	33.6	1.101	0.7804	396	0.0529	0.0142	5.159	182.7	233.1	1.596	1.286	235			
		1.329	3.9	86.6	1.069	.7614	397						5.168	182.1	283.2	1.581	1.280	236
		1.324	4.8	183.6	1.028	.7374	398						5.176	181.5	383.9	1.567	1.281	237
		1.321	5.4	383.9	1.010	.7344	399						5.185	180.8	483.4	1.565	1.291	238
		1.318	6.1	483.4	1.002	.7258	400						5.193	180.2	583.8	1.569	1.305	239
1.255	18.9	583.8	.9929	.7182	401	5.202	179.6	620.1	1.576	1.315	240							
0.0498	0.0259	2.603	283.8	333.2	1.090	0.8420	309	0.0531	0.0792	0.9231	189.1	233.1	0.8635	0.6211	169			
		2.611	282.5	383.9	1.114	.8697	310						.9249	188.0	283.2	.8398	.6051	170
		2.618	281.3	483.4	1.141	.9045	311						.9268	187.1	383.9	.8097	.5867	171
		2.626	280.0	583.8	1.151	.9224	312						.9287	186.2	483.4	.8003	.5846	172
		2.634	278.7	620.0	1.149	.9233	313						.9305	185.3	583.8	.7923	.5820	173
0.0500	0.0143	5.067	88.5	133.2	1.607	1.270	145	0.0637	0.0261	3.665	13.3	33.6	1.804	1.417	354			
		183.6	1.459	1.145	146	3.660	13.7						86.6	1.539	1.189	355		
		283.2	1.599	1.289	147	3.654	14.1						183.6	1.466	1.141	356		
		383.9	1.590	1.295	148	3.649	14.5						383.9	1.442	1.146	357		
		483.4	1.594	1.310	149	3.643	14.9						483.4	1.431	1.144	358		
0.0501	0.0259	2.951	5.6	33.6	1.517	1.155	360	0.0870	0.0439	2.873	86.0	133.2	1.239	0.9354	127			
		2.941	6.5	86.6	1.418	1.078	361						183.6	1.246	.9501	128		
		2.929	7.6	183.6	1.374	1.056	362						283.2	1.221	.9415	129		
		2.918	8.5	383.9	1.361	1.069	363						383.9	1.203	.9355	130		
		2.907	9.5	483.4	1.362	1.078	364						483.4	1.184	.9272	131		
	2.897	10.5	583.8	1.357	1.079	365	583.8	1.172	.9224	132								
	0.0406	1.706	184.9	233.1	1.065	0.8019	217	0.0969	0.0740	2.029	-0.3	33.6	1.171	0.8423	336			
		1.708	184.5	283.2	1.053	.7974	218						2.006	2.5	86.6	1.157	.8404	337
		1.710	184.0	383.9	1.037	.7938	219						1.984	5.3	183.6	1.099	.8028	338
		1.712	183.6	483.4	1.031	.7970	220						1.963	8.2	383.9	1.050	.7746	339
		1.716	182.9	583.8	1.031	.8042	221						1.942	11.0	483.4	1.025	.7523	340
		1.717	182.7	620.1	1.032	.8070	222						1.921	13.8	583.8	1.032	.7566	341
0.0502		0.00922	7.896	89.0	133.2	1.903	1.541	151	0.0973	0.0394	3.676	10.6	33.6	1.882	1.488	372		
	183.6		1.898	1.548	152	86.6	1.535	1.185						373				
	283.2		1.875	1.545	153	183.6	1.429	1.106						374				
	383.9		1.885	1.570	154	383.9	1.373	1.080						375				
	483.4		1.886	1.584	155	483.4	1.356	1.073						376				
	583.8	1.891	1.599	156	583.8	1.339	1.062	377										
	0.0412	1.864	8.5	33.6	1.201	0.8709	378	0.0979	0.0736	2.026	3.7	33.6	1.231	0.8964	414			
		1.856	9.6	86.6	1.185	.8668	379						2.021	4.4	86.6	1.149	.8334	415
		1.848	10.7	183.6	1.165	.8644	380						2.016	5.0	183.6	1.096	.8004	416
		1.840	11.8	383.9	1.145	.8661	381						2.010	5.7	383.9	1.050	.7736	417
1.832		13.0	483.4	1.135	.8622	382	2.006						6.3	483.4	1.034	.7592	418	
1.824	14.1	583.8	1.130	.8597	383	2.001	7.0	583.8	1.018	.7321	419							

TABLE I. - Continued. RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ^h	Nu _t	Run	M	Kn	Re _t	T _t	T _w	Nu _t ^h	Nu _t	Run			
0.0990	0.0259	5.199	277.5	333.2	1.279	1.014	314	0.1020	0.00916	16.91	2.0	33.6	2.653	2.194	984			
		5.208	276.7	383.9	1.351	1.086	315				16.90	2.1	86.6	2.555	2.121	985		
		5.217	276.0	483.4	1.391	1.135	316				2.2	183.6	2.505	2.101	986			
		5.226	275.3	583.8	1.406	1.158	317				16.89	2.3	383.9	2.507	2.143	987		
	5.235	274.5	620.0	1.407	1.162	318	0.00917		16.89		2.4	483.4	2.509	2.160	988			
	0.0549	2.628	72.5	133.2	1.207	0.9042			91	16.88	2.5	583.8	2.509	2.172	989			
				183.6	1.180	.8881			92	0.1024	0.0445	3.336	85.0	133.2	1.342	1.028	115	
				283.2	1.152	.8764			93					183.6	1.294	.9931	116	
				383.9	1.131	.8669	94						283.2	1.274	.9896	117		
			483.4	1.113	.8579	95						383.9	1.251	.9798	118			
			583.8	1.098	.8486	96				483.4	1.229	.9682	119					
	0.0993	0.0256	5.804	13.8	33.6	2.068	1.658		366		0.0757	1.866	185.5	233.1	1.006	0.7488	163	
5.802			13.9	86.6	1.780	1.409	367	1.873	185.3			283.2	.9663	.7188	164			
5.800			14.0	183.6	1.684	1.342	368	1.879	185.1			383.9	.9621	.7252	165			
5.798			14.1	383.9	1.645	1.336	369	1.886	184.9			483.4	.9455	.7178	166			
5.797			14.2	483.4	1.634	1.336	370	1.893	184.7			583.8	.9320	.7116	167			
5.795			14.2	583.8	1.621	1.332	371	1.900	184.5			620.1	.9244	.7062	168			
0.0997	0.0407	3.397	188.5	233.1	1.222	0.9438	211	0.1029	0.0415	3.360	280.4	333.2	1.119	0.8688	293			
		3.406	187.5	283.2	1.242	.9696	212			3.371	278.9	383.9	1.144	.8972	294			
		3.415	186.5	383.9	1.234	.9744	213			3.383	277.5	483.4	1.160	.9216	295			
		3.424	185.6	483.4	1.227	.9784	214			3.394	276.0	583.8	1.164	.9340	296			
		3.433	184.6	583.8	1.221	.9811	215			3.406	274.5	620.0	1.166	.9383	297			
		3.442	183.6	620.1	1.216	.9787	216			1.776	281.9	333.2	0.9775	0.7403	247			
0.1000	0.0569	2.707	-4.0	33.6	1.232	0.8958	390	0.1032	0.0776	1.788	278.9	383.9	.9868	.7539	248			
		2.692	-2.5	86.6	1.273	.9442	391			1.801	276.0	483.4	.9093	.6919	249			
		2.676	-1.0	183.6	1.224	.9159	392			1.816	272.3	583.8	.9002	.6904	250			
		2.661	.4	383.9	1.193	.9081	393			1.829	269.4	620.0	.8909	.6838	251			
		2.646	1.9	483.4	1.174	.8953	394			0.1039	0.0143	10.48	90.5	133.2	1.661	1.319	1035	
		2.631	3.3	583.8	1.156	.8793	395							183.6	1.627	1.482	1036	
0.1008	0.0255	5.704	89.5	133.2	1.553	1.220	522		0.0580			2.495	184.4	233.1	1.068	0.8042	181	
				183.6	1.548	1.226	523					2.498	183.9	283.2	1.083	.8243	182	
				283.2	1.559	1.253	524					2.501	183.5	383.9	1.072	.8259	183	
				383.9	1.556	1.264	525					2.504	183.0	483.4	1.061	.8248	184	
				483.4	1.550	1.269	526			2.507	182.6	583.8	1.052	.8230	185			
				583.8	1.549	1.278	527			2.510	182.1	620.1	1.047	.8214	186			
0.1009	0.0250	5.586	188.1	233.1	1.534	1.229	229	0.1069	0.0141	11.54	-2.0	33.6	2.202	1.778	935			
		5.602	187.1	283.2	1.529	1.232	230					86.6	2.180	1.774	936			
		5.618	186.0	383.9	1.523	1.241	231					183.6	2.128	1.750	937			
		5.634	185.0	483.4	1.513	1.243	232					383.9	2.117	1.776	938			
		5.650	183.9	583.8	1.511	1.251	233					483.4	2.110	1.782	939			
		5.666	182.8	620.1	1.507	1.250	234					583.8	2.103	1.786	940			
0.1010	0.00917	15.92	90.0	133.2	1.996	1.626	1065	0.1614	0.0613	3.948	6.0	33.6	1.543	1.179	324			
				183.6	2.194	1.821	1066			3.934	6.9	86.6	1.437	1.095	325			
				283.2	2.278	1.920	1067			3.919	7.9	183.6	1.355	1.038	326			
				383.9	2.310	1.968	1068			3.904	8.9	383.9	1.283	.9957	327			
				483.4	2.329	2.000	1069			3.890	9.9	483.4	1.258	.9789	328			
				583.8	2.337	2.020	1070			3.875	10.9	583.8	1.235	.9609	329			
	0.0749	1.960	79.5	132.0	1.127	0.8328	13	0.1956	0.0139	21.29	-2.0	33.6	2.919	2.441	923			
				183.0	1.064	.7836	14					86.6	2.790	2.339	924			
				234.5	1.050	.7776	15					183.6	2.680	2.264	925			
				285.1	1.023	.7585	16					383.9	2.611	2.241	926			
				332.6	1.016	.7565	17					483.4	2.603	2.248	927			
				386.5	.9997	.7457	18					583.8	2.576	2.235	928			
	0.0251	11.75	-2.0	33.6	2.153	1.733	917		0.0251	11.75	-2.0	33.6	2.153	1.733	917			
				86.6	2.172	1.767	918			11.76	-2.2	86.6	2.172	1.767	918			
				183.6	2.076	1.702	919			-2.4	183.6	2.076	1.702	919				
				383.9	2.029	1.692	920			11.77	-2.6	383.9	2.029	1.692	920			
				483.4	2.001	1.679	921			11.78	-2.8	483.4	2.001	1.679	921			
				583.8	1.983	1.672	922			-5.0	583.8	1.983	1.672	922				
0.1012	0.0411	3.368	269.4	333.2	1.076	0.8283	299	0.1957	0.0746	3.909	11.4	33.6	1.574	1.207	330			
		3.367	269.5	383.9	1.133	.8864	300			3.894	12.4	86.6	1.375	1.039	331			
		3.365	269.8	483.4	1.161	.9218	301			3.880	13.4	183.6	1.290	.9792	332			
		3.364	270.0	583.8	1.169	.9386	302			3.866	14.3	383.9	1.213	.9314	333			
		3.363	270.1	620.0	1.172	.9441	303			3.852	15.3	483.4	1.186	.9121	334			
										3.838	16.3	583.8	1.164	.8938	335			
0.1019	0.0255	5.780	87.0	133.2	1.592	1.256	139	0.1972	0.0735	3.619	259.0	333.2	1.087	0.8386	252			
				183.6	1.623	1.295	140			3.622	258.6	383.9	1.091	.8479	253			
				283.2	1.590	1.281	141			3.625	258.3	483.4	1.079	.8465	254			
				383.9	1.566	1.273	142			3.628	257.9	583.8	1.070	.8457	255			
				483.4	1.556	1.274	143			3.632	257.5	620.0	1.066	.8444	256			
				583.8	1.543	1.272	144			0.1986	0.00908	33.03	-3.5	33.6	3.458	2.942	947	
	0.0766	1.928	85.0	133.2	1.112	0.8202	37	0.00909	33.00			-3.2	86.6	3.334	2.846	948		
				183.6	1.057	.7782	38		32.97			-2.9	183.6	3.209	2.760	949		
				233.1	1.038	.7673	39		0.00910			32.94	-2.6	383.9	3.181	2.779	950	
				283.2	1.023	.7598	40					0.00911	32.91	-2.3	483.4	3.163	2.779	951
				333.2	1.010	.7528	41						32.88	-2.0	583.8	3.163	2.794	952
				383.9	.9956	.7433	42											
		433.0	.9823	.7343	43													
		483.4	.9722	.7276	44													
		533.0	.9625	.7206	45													
		583.8	.9480	.7081	46													

TABLE I. - Continued. RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ^h	Nu _t	Run	M	Kn	Re _t	T _t	T _w	Nu _t ^h	Nu _t	Run																																							
0.1987	0.0400	6.708	267.9	333.2	1.358	1.086	304	0.2050	0.0407	7.196	91.8	133.2	1.702	1.357	262																																							
		6.720	267.1	383.9	1.409	1.139	305			7.185	92.3	183.6	1.652	1.322	263																																							
		6.732	266.4	483.4	1.425	1.165	306			7.174	92.7	283.2	1.616	1.306	264																																							
		6.743	265.6	583.8	1.417	1.168	307			7.164	93.2	383.9	1.587	1.293	265																																							
		6.755	264.9	620.0	1.419	1.173	308			7.153	93.7	483.4	1.562	1.281	266																																							
																0.1989	0.00916	31.09	90.0	133.2	2.496	2.088	1053	0.2068	0.0769	3.856	88.0	132.0	1.465	1.140	25																							
																				183.6	2.798	2.383	1054					183.0	1.321	1.018	26																							
																				283.2	2.904	2.506	1055					234.5	1.262	.9719	27																							
																				383.9	2.933	2.554	1056					285.1	1.229	.9485	28																							
483.4	2.942	2.580	1057	332.6	1.197	.9248	29																																															
																583.8	2.951	2.602	1058	386.5	1.168	.9036	30																															
																133.2	1.464	1.138	97	437.3	1.147	.8879	31																															
																183.6	1.359	1.052	98	488.0	1.130	.8761	32																															
																283.2	1.374	1.081	99	538.5	1.124	.8735	33																															
0.1996	0.0559	5.147	79.0	283.2	1.374	1.081	99																																															
				383.9	1.335	1.057	100									590.2	1.119	.8724	34																																			
				483.4	1.302	1.036	101									640.4	1.103	.8592	35																																			
				583.8	1.277	1.020	102																																															
0.1997	0.0745	3.840	90.0	133.2	1.412	1.093	49	0.2072	0.0570	4.949	183.5	233.1	1.382	1.089	187																																							
				183.6	1.250	.9540	50					4.960	182.7	283.2	1.273	.9971	188																																					
				233.1	1.221	.9351	51					4.970	182.0	383.9	1.313	1.047	189																																					
				283.2	1.201	.9231	52					4.980	181.2	483.4	1.283	1.029	190																																					
				333.2	1.185	.9145	53					4.990	180.5	583.8	1.263	1.020	191																																					
				383.9	1.162	.8979	54					5.000	179.7	620.1	1.251	1.011	192																																					
				433.0	1.140	.8826	55					0.2081	0.0754	3.793	179.0	233.1	1.128	0.8584	157																																			
				483.4	1.123	.8700	56									3.801	178.7	283.2	1.162	.8961	158																																	
				533.0	1.112	.8634	57									3.809	178.4	383.9	1.133	.8808	159																																	
				583.8	1.110	.8639	58									3.817	178.1	483.4	1.113	.8715	160																																	
620.1	1.090	.8467	59	3.825	177.8	583.8	1.091	.8591	161																																													
				3.833	177.5	620.1	1.079	.8499	162																																													
0.1998	0.0254	10.79	192.0	620.1	1.792	1.518	748	0.2357	0.0435	7.739	85.8					133.2	1.710	1.363	121																																			
																183.6	1.657	1.326	122																																			
																283.2	1.610	1.299	123																																			
																383.9	1.568	1.275	124																																			
																483.4	1.537	1.256	125																																			
																583.8	1.510	1.240	126																																			
0.1999	0.0402	7.503	-2.0	33.6	1.776	1.388	857	0.2921	0.0252	15.22	284.0	333.2	1.675	1.378	727																																							
		7.499	-1.8	86.6	1.742	1.371	858									0.2926	0.0391	10.11	194.5	233.1	1.533	1.228	611																															
		7.494	-1.6	183.6	1.675	1.331	859																	0.2926	0.0392	10.11	194.8	283.2	1.649	1.343	612																							
		7.490	-1.4	383.9	1.628	1.316	860																									0.2926	0.0392	10.11	194.8	383.9	1.633	1.344	613															
																0.2025	0.0411	6.713	194.1	233.1	1.547	1.240	205																	0.2959	0.00911	48.30	-2.0	583.8	3.584	3.196	983							
																								6.727	193.3	283.2	1.545	1.247	206	0.2959	0.00912																	48.26	-1.7	483.4	3.585	3.181	982	
																								6.740	192.5	383.9	1.512	1.230	207			0.2959	0.00913	48.22	-1.4	383.9	3.598	3.175	981															
																								6.754	191.8	483.4	1.488	1.220	208																									0.2959
6.768	191.0	583.8	1.465	1.209	209	0.2959	0.00913	48.14	-.8	86.6	3.788	3.273	979																																									
																								0.2025	0.0411	6.713	194.1	233.1	1.547	1.240	205									0.2964	0.0402	10.96	-3.0	33.6	1.982	1.577	839							
																																6.727	193.3	283.2	1.545	1.247	206	0.2964	0.0402									10.96	-2.9	86.6	1.913	1.529	840	
																																6.740	192.5	383.9	1.512	1.230	207																	0.2964
						6.754	191.8	483.4	1.488	1.220	208	0.2964	0.0402																			10.96	-2.7	383.9	1.816	1.493	842																	
6.768	191.0	583.8	1.465	1.209	209	0.2964	0.0402	10.96	-2.6	483.4	1.771			1.462	843																																							
																										0.2032	0.0567	4.803	271.6	333.2	1.217							0.9572	268	0.2972	0.00901	49.08	-4.0	33.6	4.035	3.481	953							
																																																4.819	270.1	383.9	1.224	.9701	269	0.2972
												4.836	268.6																			483.4	1.213	.9701	270	0.2972	0.00902											49.02	-3.6	183.6	3.703	3.225	955	
						4.853	267.2	583.8	1.205	.9710	271	0.2972	0.00902	48.99	-3.4																	383.9	3.631	3.206	956																			
4.870	265.7	620.0	1.206	.9746	272	0.2972	0.00903	48.97	-3.2	483.4	3.605					3.200	957																																					
																												0.2034	0.0582	5.237	7.8							33.6	1.665	1.290	384	0.2972	0.00903	48.94	-3.0	583.8	3.611							3.221
																																				5.222	8.6											86.6	1.540	1.189	385			
												5.209	9.2	183.6	1.454																	1.129	386																					
						5.193	10.0	383.9	1.384	1.091	387																																											
5.179	10.7	483.4	1.350	1.067	388																																																	
																5.175	10.8	583.8	1.326	1.049	389																																	
																4.052	-0.7	33.6	1.458	1.100	408																																	
																4.037	.3	86.6	1.366	1.030	409																																	
																4.021	1.3	183.6	1.287	.9749	410																																	
																4.006	2.3	383.9	1.218	.9320	411																																	
																3.991	3.2	483.4	1.192	.9127	412																																	
																3.976	4.2	583.8	1.161	.8847	413																																	

TABLE I. - Continued. RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ¹	Nu _t	Run	M	Kn	Re _t	T _t	T _w	Nu _t ¹	Nu _t	Run												
0.2975	0.0752	5.172	282.7	333.2	1.234	0.9730	257	0.3088	0.0750	5.536	181.0	233.1	1.295	1.010	175												
				383.9	1.214	.9614	258			5.542	180.8	283.2	1.270	.9949	176												
				483.4	1.178	.9387	259			5.548	180.6	383.9	1.250	.9888	177												
				583.8	1.159	.9299	260			5.554	180.4	483.4	1.218	.9698	178												
				620.0	1.153	.9271	261			5.559	180.2	583.8	1.188	.9501	179												
0.2979	0.0550	7.674	82.3	133.2	1.617	1.278	103	0.3183	0.0444	10.09	88.5	133.2	1.763	1.413	486												
				183.6	1.581	1.256	104					183.6	1.790	1.448	487												
				283.2	1.526	1.222	105					283.2	1.753	1.432	488												
				383.9	1.479	1.191	106					383.9	1.730	1.426	489												
				483.4	1.437	1.163	107					483.4	1.704	1.414	490												
0.2980	0.0142	29.57	89.0	133.2	2.434	2.031	1023	0.3948	0.00919	59.46	88.0	133.2	3.334	2.871	1071												
				183.6	2.674	2.268	1024					183.6	3.549	3.089	1072												
				283.2	2.715	2.329	1025					283.2	3.644	3.206	1073												
				383.9	2.762	2.393	1026					383.9	3.672	3.254	1074												
				483.4	2.758	2.405	1027					483.4	3.683	3.284	1075												
0.2983	0.0142	31.23	-3.0	33.6	3.172	2.675	929	0.3961	0.0242	23.94	-8.0	33.6	2.699	2.237	881												
				86.6	3.151	2.676	930					86.6	2.684	2.240	882												
				183.6	3.044	2.605	931					23.96	-8.2	183.6	2.586	2.177	883										
				383.9	2.990	2.598	932					-8.3	383.9	2.488	2.124	884											
				483.4	2.962	2.589	933					23.97	-8.4	483.4	2.523	2.172	885										
0.2983	0.0142	31.30	-3.8	483.4	2.962	2.589	933	0.3961	0.0242	23.98	-8.5	583.8	2.406	2.073	886												
				583.8	2.941	2.582	934					23.98	-8.5	583.8	2.406	2.073	886										
				15.91	194.4	583.8	2.059					1.766	741	0.3977	0.0410	14.15	-6.0	33.6	2.174	1.753	833						
				15.92	194.0	620.1	2.039					1.751	742					14.14	-5.9	86.6	2.097	1.698	834				
				15.86	196.0	233.1	1.776					1.452	737					-5.8	183.6	2.005	1.636	835					
0.2987	0.00922	45.74	89.0	133.2	2.911	2.475	1059	0.3977	0.0410	14.13	-5.7	383.9	1.926					1.596	836								
				183.6	3.236	2.794	1060					14.13	-5.7					383.9	1.926	1.596	836						
				283.2	3.314	2.893	1061					14.13	-5.7	383.9	1.926	1.596	836										
				383.9	3.339	2.938	1062					14.13	-5.7	383.9	1.926	1.596	836										
				483.4	3.339	2.956	1063					14.13	-5.7	383.9	1.926	1.596	836										
0.2990	0.0739	5.714	80.4	583.8	3.356	2.988	1064	0.3982	0.0776	7.082	91.0	133.2	1.498	1.172	426												
				133.2	1.437	1.115	61					183.6	1.369	1.063	427												
				183.6	1.361	1.055	62					283.2	1.376	1.085	428												
				233.1	1.330	1.035	63					383.9	1.332	1.057	429												
				283.2	1.311	1.025	64					483.4	1.295	1.032	430												
0.2990	0.0739	5.714	80.4	333.2	1.298	1.019	65	0.3982	0.0776	7.082	91.0	583.8	1.260	1.007	431												
				383.9	1.268	.9970	66					183.6	1.369	1.063	427												
				433.0	1.245	.9796	67					283.2	1.376	1.085	428												
				483.4	1.226	.9662	68					383.9	1.332	1.057	429												
				533.0	1.210	.9553	69					483.4	1.295	1.032	430												
0.2994	0.0399	9.843	284.0	583.8	1.194	.9438	70	0.3986	0.00911	63.76	-4.0	483.4	3.919	3.500	994												
				620.1	1.180	.9328	71					583.8	1.260	1.007	431												
				133.2	1.437	1.115	61					.00912	63.67	-3.5	383.9	3.915	3.477	993									
				183.6	1.361	1.055	62					.00913	63.58	-3.0	183.6	4.017	3.523	992									
				233.1	1.330	1.035	63					.00914	63.49	-2.5	86.6	4.166	3.628	991									
0.2994	0.0399	9.851	283.5	433.0	1.245	.9796	67	0.3986	0.00911	63.40	-2.0	33.6	4.459	3.881	990												
				483.4	1.226	.9662	68					33.6	4.459	3.881	990												
				533.0	1.210	.9553	69					33.6	4.459	3.881	990												
				583.8	1.194	.9438	70					33.6	4.459	3.881	990												
				620.1	1.180	.9328	71					33.6	4.459	3.881	990												
0.2994	0.0399	9.859	283.0	620.0	1.558	1.304	701	0.3987	0.0766	7.556	0.5	33.6	1.713	1.332	767												
				133.2	1.442	1.163	697					0.3987	0.0766	7.556	0.5	33.6	1.713	1.332	767								
				1513	1.236	1.364	698									0.3987	0.0766	7.556	0.5	33.6	1.713	1.332	767				
				133.2	1.442	1.163	697													0.3987	0.0766	7.556	0.5	33.6	1.713	1.332	767
				1513	1.236	1.364	698																	0.3987	0.0766	7.556	0.5
0.3005	0.0254	16.67	89.5	133.2	2.184	1.800	534	0.3987	0.0766	7.556	0.5																
				183.6	2.190	1.818	535					0.3987	0.0766	7.556	0.5												
				283.2	2.183	1.832	536									0.3987	0.0766	7.556	0.5								
				383.9	2.159	1.827	537													0.3987	0.0766	7.556	0.5				
				483.4	2.142	1.824	538																	0.3987	0.0766	7.556	0.5
0.3012	0.0253	17.63	0.4	583.8	2.132	1.827	539	0.3987	0.0766	7.556	0.5																
				133.2	2.184	1.800	534					0.3987	0.0766	7.556	0.5												
				183.6	2.190	1.818	535									0.3987	0.0766	7.556	0.5								
				283.2	2.183	1.832	536													0.3987	0.0766	7.556	0.5				
				383.9	2.159	1.827	537																	0.3987	0.0766	7.556	0.5
0.3012	0.0253	17.64	.2	483.4	2.142	1.824	538	0.3987	0.0766	7.556	0.5																
				583.8	2.132	1.827	539					0.3987	0.0766	7.556	0.5												
				133.2	2.184	1.800	534									0.3987	0.0766	7.556	0.5								
				183.6	2.190	1.818	535													0.3987	0.0766	7.556	0.5				
				283.2	2.183	1.832	536																	0.3987	0.0766	7.556	0.5
0.3012	0.0253	17.65	0	383.9	2.159	1.827	537	0.3987	0.0766	7.556	0.5																
				483.4	2.142	1.824	538					0.3987	0.0766	7.556	0.5												
				583.8	2.132	1.827	539									0.3987	0.0766	7.556	0.5								
				133.2	2.184	1.800	534													0.3987	0.0766	7.556	0.5				
				183.6	2.190	1.818	535																	0.3987	0.0766	7.556	0.5
0.3019	0.0591	7.574	0	283.2	2.183	1.832	536	0.3987	0.0766	7.556	0.5																
				383.9	2.159	1.827	537					0.3987	0.0766	7.556	0.5												
				483.4	2.142	1.824	538									0.3987	0.0766	7.556	0.5								
				583.8	2.132	1.827	539													0.3987	0.0766	7.556	0.5				
				133.2	2.184	1.800	534																	0.3987	0.0766	7.556	0.5
0.3019	0.0591	7.570	.2	183.6	2.190	1.818	535	0.3987	0.0766	7.556	0.5																
				283.2	2.183	1.832	536					0.3987	0.0766	7.556	0.5												
				383.9	2.159	1.827	537									0.3987	0.0766	7.556	0.5								
				483.4	2.142	1.824	538													0.3987	0.0766	7.556	0.5				
				583.8	2.132	1.827	539																	0.3987	0.0766	7.556	0.5
0.3019	0.0591	7.570	.2	133.2	2.184	1.800	534	0.3987	0.0766	7.556	0.5																
				183.6	2.190	1.818	535					0.3987	0.0766	7.556	0.5												
				283.2	2.183	1.832	536									0.3987	0.0766	7.556	0.5								
				383.9	2.159	1.827	537													0.3987	0.0766	7.556	0.5				
				483.4	2.142	1.824	538																	0.3987	0.0766	7.556	0.5
0.3019	0.0591	7.570	.2	583.8	2.132	1.827	539	0.3987	0.0766	7.556	0.5																
				133.2	2.184	1.800	534					0.3987	0.0766	7.556	0.5												
				183.6	2.190	1.818	535									0.3987	0.0766	7.556	0.5								
				283.2	2.183	1.832	536													0.3987	0.0766	7.556	0.5				
				383.9	2.159	1.827	537																	0.3987	0.0766	7.556	0.5
0.3019	0.0591	7.570	.2	483.4	2.142	1.824	538	0.3987	0.0766	7.556	0.5																
				583.8	2.132	1.827	539					0.3987	0.0766	7.556	0.5												
				133.2	2.184	1.800	534									0.3987	0.0766	7.556	0.5								

TABLE I. - Continued. RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ¹	Nu _t	Run	M	Kn	Re _t	T _t	T _w	Nu _t ¹	Nu _t	Run																										
0.4007	0.0565	9.116	281.5	333.1	1.241	0.9801	666	0.4931	0.00910	77.03	-5.0	33.6	4.587	4.002	996																										
				383.9	1.349	1.085	667	0.4951	0.0143	46.77	87.0	133.2	2.698	2.277	1047																										
				483.4	1.399	1.143	668					183.6	3.044	2.615	1048																										
				583.8	1.398	1.151	669					283.2	3.145	2.735	1049																										
				620.0	1.386	1.144	670					383.9	3.158	2.768	1050																										
0.4008	0.0408	12.99	192.2	583.8	1.720	1.447	621	0.4965	0.0143	49.35	-3.0	483.4	3.149	2.777	1051																										
			192.0	620.1	1.712	1.444	622					583.8	3.136	2.780	1052																										
	0.0409	12.97	193.0	233.1	1.647	1.333	617					33.6	3.605	3.081	959																										
			192.8	283.2	1.705	1.395	618					86.6	3.520	3.023	960																										
			12.98	192.6	383.9	1.739	1.442					619	183.6	3.469	3.007	961																									
192.4	483.4	1.732		1.448	620	383.9	3.384					2.973	962																												
0.4010	0.0256	21.64	89.0	133.2	2.355	1.959	540					0.4968	0.0249	28.31	-6.0	483.4	3.357	2.966	963																						
				183.6	2.384	1.999	541									583.8	3.315	2.940	964																						
				283.2	2.359	1.996	542	33.6	2.871	2.397	893																														
				383.9	2.339	1.996	543	86.6	2.788	2.339	894																														
				483.4	2.309	1.982	544	183.6	2.702	2.286	895																														
583.8	2.289	1.976	545	383.9	2.578	2.211	896																																		
0.4013	0.0402	12.84	282.0	333.2	1.350	1.080	702	0.4974	0.0398	17.80	-8.0	483.4	2.525	2.175	897																										
				383.9	1.568	1.287	703					583.8	2.484	2.148	898																										
				483.4	1.652	1.377	704					33.6	2.270	1.842	845																										
				583.8	1.678	1.412	705					86.6	2.217	1.809	846																										
				620.0	1.677	1.414	706					17.78	-7.6	183.6	2.146	1.768	847																								
0.4024	0.0749	6.911	283.0	333.2	1.027	0.7852	646					17.77	-7.4	383.9	2.050	1.713	848																								
				6.908	283.2	383.9	1.141	.8950	647	17.76	-7.2	483.4	2.011	1.689	849																										
				6.905	283.5	483.4	1.185	.9451	648	17.75	-7.0	583.8	1.986	1.675	850																										
				6.902	283.8	583.8	1.186	.9550	649	0.4981	0.0255	26.34	87.0	133.2	2.377	1.980	546																								
				0.0750	6.899	284.0	620.0	1.185	0.9571					650	183.6	2.467	2.077	547																							
283.2	2.464	2.095	548																																						
383.9	2.445	2.096	549																																						
483.4	2.418	2.086	550																																						
0.4028	0.0742	7.503	91.3	133.2	1.494	1.167	73	0.4986	0.0403					16.70	84.0	583.8	2.387	2.068	551																						
				183.6	1.458	1.144	74			133.2	1.936	1.572	498																												
				233.1	1.437	1.134	75			183.6	1.971	1.616	499																												
				283.2	1.405	1.111	76			283.2	1.967	1.632	500																												
				333.2	1.377	1.092	77			383.9	1.885	1.571	501																												
383.9	1.258	.9878	78	483.4	1.907	1.604	502																																		
0.4032	0.0250	20.74	282.0	433.0	1.316	1.047	79	0.4992	0.0388	18.49	-24.0	583.8	1.877	1.587	503																										
				483.4	1.288	1.025	80					33.6	2.295	1.863	869																										
				533.0	1.269	1.011	81					18.46	-23.6	86.6	2.274	1.860	870																								
				583.8	1.251	.9977	82					18.44	-23.2	183.6	2.132	1.752	871																								
				620.1	1.240	.9893	83					18.42	-22.8	383.9	2.027	1.688	872																								
0.4032	0.0251	20.68	283.7	483.4	2.071	1.768	734					0.4998	0.0573	11.26	190.0	233.1	1.283	1.001	581																						
				283.8	583.8	2.113	1.820	735	283.2	1.476	1.185					582																									
				20.67	284.0	620.0	2.120	1.831	736	383.9	1.499					1.220	583																								
	0.0141	38.02	184.5	233.1	2.215	1.857	1113	483.4	1.492	1.225	584																														
								37.99	184.9	283.2	2.583	2.211	1114	583.8	1.480	1.223	585																								
37.96								185.3	383.9	2.848	2.480	1115	620.1	1.476	1.223	586																									
37.93								185.7	483.4	2.862	2.510	1116	0.5005	0.0254	25.45	188.0	233.1	2.019	1.677	755																					
37.90	186.1	583.8	2.855	2.518	1117	25.41	188.8	283.2	2.150	1.808	756																														
37.87	186.5	620.1	2.860	2.527	1118	25.37	189.6	383.9	2.226	1.896	757																														
0.4072	0.0585	10.10	-2.0	33.6	1.843	1.451	809	0.0255	25.33	190.4	483.4	2.258					1.941	758																							
																			10.09	-1.6	183.6	1.699	1.354	811	25.29	191.2	583.8	2.271	1.966	759											
													10.08	-1.4	383.9	1.602			1.293	812	25.26	192.0	620.1	2.283	1.982	760															
													10.07	-1.2	483.4	1.558			1.262	813	0.5006	0.0401	15.62	280.0	333.2	1.403	1.128	707													
													0.0587	10.07	-1.0	583.8			1.519	1.232					814	383.9	1.711	1.419	708												
15.63	281.0	383.9	1.711	1.419	709																																				
15.60	281.0	483.4	1.728	1.448	709																																				
15.57	282.0	583.8	1.733	1.464	710																																				
0.4074	0.0577	9.334	192.0	15.55	283.0	620.0	1.740	1.474	711	0.5010	0.0565	11.11	282.0	333.2	1.327	1.059	676																								
				233.1	1.346	1.058	599	383.9	1.433					1.163	677																										
				283.2	1.277	1.002	600	483.4	1.456					1.196	678																										
				383.9	1.454	1.178	601	583.8	1.448					1.198	679																										
				483.4	1.445	1.181	602	620.0	1.441					1.195	680																										
0.4415	0.0570	10.13	194.5	583.8	1.430	1.177	603	0.5016	0.0761	9.316	0.5	33.6	1.828	1.439	773																										
				620.1	1.422	1.172	604					86.6	1.654	1.294	774																										
				10.17	192.4	283.2	1.290					1.014	553	183.6	1.544	1.213	775																								
				10.21	190.3	383.9	1.301					1.037	554	383.9	1.437	1.139	776																								
				10.25	188.2	483.4	1.275					1.023	555	483.4	1.397	1.110	777																								
0.4717	0.0647	9.212	280.0	583.8	1.428	1.009	557	0.5048	0.0411	15.80	191.0	620.1	1.780	1.508	629																										
				10.30	186.1	583.8	1.260					1.018	556	15.75	192.6	283.2	1.765	1.451	624																						
				10.34	184.0	620.1	1.248					1.009	557	15.76	192.2	383.9	1.836	1.533	625																						
				0.0648	9.200	280.8	583.8					1.241	1.006	644	15.78	191.8	483.4	1.829	1.539	626																					
															9.190	281.5	483.4	1.249	1.004	643	15.79	191.4	583.8	1.788	1.512	628															
0.0649	9.179	282.2	383.9												1.230	0.9761	642	0.0412	15.75	192.6	283.2	1.765	1.451	624																	
								0.0650	9.167	283.0	333.2														1.085	0.8381	641	0.0413	15.74	193.0	233.1	1.653	1.340	623							
				0.00910	75.19	-5.0	33.6					4.549	3.966	995																					0.0413	15.74	193.0	233.1	1.653	1.340	623
183.6	4.267	3.760	998												0.0413	15.74	193.0	233.1	1.653	1.340	623																				
								383.9	4.161	3.712	999											0.0413	15.74	193.0	233.1	1.653	1.340	623													
				483.4	4.128	3.700	1000					0.0413	15.74	193.0															233.1	1.653	1.340	623									

TABLE I. - Continued. RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ^{''}	Nu _t	Run	M	Kn	Re _t	T _t	T _w	Nu _t ^{''}	Nu _t	Run			
0.5051	0.0578	11.73	89.5	133.2	1.767	1.418	450	0.5977	0.0143	57.24	-3.8	86.6	3.677	3.171	966			
				183.6	1.751	1.395	451			57.29	-4.1	183.6	3.605	3.136	967			
				283.2	1.660	1.347	452			57.34	-4.4	383.9	3.518	3.102	969			
				383.9	1.608	1.314	453			57.39	-4.7	483.4	3.475	3.078	970			
				483.4	1.566	1.286	454			57.44	-5.0	583.8	3.429	3.051	971			
				583.8	1.529	1.260	455			0.0144	57.19	-3.5	33.6	3.758	3.226	965		
0.5056	0.0570	12.55	-4.0	33.6	2.068	1.657	803	0.5983	0.0750	9.696	277.2	583.8	1.244	1.009	654			
				86.6	1.917	1.534	804			9.699	277.0	620.0	1.233	1.002	655			
				183.6	1.764	1.414	805											
				383.9	1.676	1.363	806			0.0751	9.683	278.0	333.2	1.108	0.8598	651		
				483.4	1.622	1.322	807				9.686	277.8	383.9	1.210	.9584	652		
				583.8	1.579	1.289	808			9.691	277.5	483.4	1.250	1.006	653			
0.5061	0.0141	46.30	182.0	233.1	2.392	2.023	1119	0.5996	0.0144	54.48	84.0	133.2	2.880	2.448	1083			
				283.2	2.716	2.336	1120					183.6	3.148	2.714	1084			
				383.9	2.970	2.596	1121					283.2	3.278	2.861	1085			
	0.0142	46.14	183.8	483.4	3.012	2.653	1122					383.9	3.320	2.922	1086			
				46.09	184.4	583.8	1123					483.4	3.302	2.923	1087			
		46.04	185.0	620.1	3.013	2.673	1124					583.8	3.297	2.934	1088			
0.5087	0.0556	11.79	184.0	620.1	1.265	1.025	563	0.6001	0.0569	14.51	-6.0	33.6	2.100	1.687	797			
				185.2	583.8	1.273	1.031					562	86.6	1.981	1.593	798		
				186.4	483.4	1.300	1.046					561	183.6	1.871	1.514	799		
				187.6	383.9	1.330	1.064					560	383.9	1.754	1.437	800		
				188.8	283.2	1.218	.9488					559	483.4	1.697	1.393	801		
		11.66	190.0	233.1	1.237	.9583	558							583.8	1.657	1.363	802	
0.5195	0.00924	75.32	86.0	133.2	3.480	3.009	1077	0.6005	0.0775	10.10	89.5	133.2	1.611	1.275	438			
				183.6	3.692	3.225	1078					183.6	1.517	1.199	439			
				283.2	3.892	3.442	1079					283.2	1.441	1.146	440			
				383.9	3.914	3.486	1080					383.9	1.394	1.115	441			
				483.4	3.919	3.510	1081					483.4	1.345	1.079	442			
												583.8	1.305	1.050	443			
0.5214	0.0773	9.012	89.0	133.2	1.626	1.289	432	0.6011	0.0406	18.49	189.0	233.1	1.711	1.393	630			
				183.6	1.510	1.192	433					18.47	189.6	283.2	1.902	1.578	631	
				283.2	1.431	1.136	434					18.45	190.2	383.9	1.880	1.574	632	
				383.9	1.398	1.118	435					18.43	190.8	483.4	1.851	1.560	633	
				483.4	1.354	1.087	436											
				583.8	1.307	1.051	437			0.0408	18.41	191.4	583.8	1.818	1.541	634A		
0.5651	0.0563	13.96	-4.5	33.6	2.136	1.720	791	0.6017	0.0742	11.13	-5.0	33.6	1.819	1.431	761			
				86.6	1.993	1.604	792					-4.8	86.6	1.703	1.338	762		
				183.6	1.872	1.515	793											
				383.9	1.755	1.437	794					0.0743	11.12	-4.6	183.6	1.612	1.275	763
				483.4	1.715	1.410	795						11.12	-4.4	383.9	1.489	1.188	764
				583.8	1.667	1.373	796			11.11	-4.2	483.4	1.444	1.154	765			
0.5906	0.0398	18.09	276.0	333.2	1.555	1.269	712	0.6030	0.0565	12.94	280.0	333.2	1.341	1.073	681			
				383.9	1.697	1.407	713					383.9	1.450	1.179	682			
				483.4	1.765	1.483	714					483.4	1.469	1.209	683			
	0.0400	17.99	279.0	583.8	1.768	1.498	715					583.8	1.465	1.215	684			
				17.95	280.5	583.8	1.768					1.498	715	620.0	1.465	1.218	685	
	0.0401	17.91	282.0	620.0	1.775	1.509	716											
0.5915	0.0250	29.73	180.0	233.1	1.935	1.599	1095	0.6049	0.0400	20.79	-10.0	383.9	2.095	1.756	854			
				283.2	2.139	1.798	1096					483.4	2.048	1.724	855			
				383.9	2.330	1.994	1097					583.8	2.006	1.694	856			
	0.0251	29.68	180.8	383.9	2.330	1.994	1097					0.0401	20.73	-9.0	33.6	2.306	1.876	851
				29.66	181.2	483.4	2.365								2.042	1098	20.75	-9.2
		29.64	181.6	583.8	2.360	2.050	1099			20.77	-9.6	183.6	2.184	1.803	853			
		29.62	182.0	620.1	2.344	2.040	1100											
0.5926	0.0247	33.07	-8.8	483.4	2.596	2.242	903	0.6050	0.0405	19.48	83.5	133.2	1.983	1.616	504			
				583.8	2.565	2.225	904					183.6	2.013	1.656	505			
				620.1	2.344	2.040	1100					283.2	2.006	1.668	506			
	0.0248	33.00	-8.0	33.6	2.930	2.453	899					383.9	1.969	1.650	507			
				33.01	-8.2	86.6	2.875					2.421	900	483.4	1.945	1.640	508	
		33.03	-8.4	183.6	2.751	2.333	901			583.8	1.898	1.607	509					
		33.05	-8.6	383.9	2.646	2.275	902											
0.5933	0.0253	30.76	82.0	133.2	2.223	1.837	1005	0.6142	0.0237	35.49	-10.0	33.6	2.855	2.383	905			
				183.6	2.422	2.035	1006					86.6	2.941	2.482	906			
				283.2	2.124	.9677	1007					183.6	2.845	2.420	907			
				383.9	2.481	2.130	1008					383.9	2.717	2.342	908			
				483.4	2.458	2.123	1009					483.4	2.643	2.287	909			
				583.8	2.431	2.111	1010					583.8	2.572	2.232	910			
0.5943	0.0587	13.25	83.0	133.2	1.606	1.271	468	0.6897	0.0250	34.93	81.0	133.2	2.291	1.902	1011			
				183.6	1.679	1.348	469					183.6	2.475	2.085	1012			
				283.2	1.649	1.337	470					283.2	2.541	2.169	1013			
				383.9	1.611	1.316	471					383.9	2.547	2.193	1014			
				483.4	1.573	1.292	472					483.4	2.522	2.184	1015			
				583.8	1.538	1.268	473					583.8	2.484	2.162	1016			
0.5958	0.0571	13.07	188.8	233.1	1.460	1.163	587	0.6920	0.0255	32.85	179.6	283.2	2.274	1.924	1102			
				283.2	1.508	1.214	588					32.88	179.2	383.9	2.364	2.027	1103	
				383.9	1.528	1.248	589					32.90	178.8	483.4	2.369	2.047	1104	
				483.4	1.520	1.252	590					32.93	178.4	583.8	2.361	2.052	1105	
				583.8	1.498	1.241	591					32.96	178.0	620.1	2.363	2.058	1106	
				620.1	1.501	1.247	592			0.0256	32.83	180.0	233.1	2.024	1.682	1101		

TABLE I. - Concluded. RESULTS OF STUDY OF HEAT TRANSFER FROM CYLINDERS IN SUBSONIC SLIP FLOW

M	Kn	Re _t	T _t	T _w	Nu _t ^h	Nu _t	Run	M	Kn	Re _t	T _t	T _w	Nu _t ^h	Nu _t	Run		
0.6932	0.0557	15.05	186.0	233.1	1.502	1.202	593	0.7635	0.0559	15.59	275.2	583.8	1.465	1.216	695		
				283.2	1.542	1.247	594										
				383.9	1.524	1.245	595										
				483.4	1.513	1.245	596										
				583.8	1.493	1.236	597										
0.7008	0.0408	20.73	184.0	620.1	1.823	1.550	640	0.7714	0.0759	11.57	276.0	333.2	1.173	0.9194	661		
				185.5	1.841	1.562	639										
				187.0	1.874	1.582	638										
				188.5	1.876	1.571	637										
				188.0	233.1	1.735	1.415									635	
0.7012	0.0573	15.42	81.3	133.2	1.671	1.330	474	0.7799	0.0570	15.99	183.0	233.1	1.430	1.136	605		
				183.6	1.705	1.372	475										
				283.2	1.685	1.371	476										
				383.9	1.647	1.351	477										
				483.4	1.607	1.325	478										
0.7019	0.0761	12.19	-3.7	183.6	1.568	1.235	781	0.7827	0.0772	11.83	185.0	233.1	1.234	0.9575	575		
				383.9	1.454	1.156	782										
				483.4	1.407	1.120	783										
				12.20	-4.0	583.8	1.368									784	
				0.7062	12.18	-3.5	33.6									1.746	1.365
0.7035	0.0400	20.55	274.0	333.2	1.616	1.326	717	0.7831	0.0386	26.32	-27.2	86.6	2.368	1.949	876		
				383.9	1.748	1.455	718										
				20.44	277.0	483.4	1.787									1.504	719
				20.39	278.3	583.8	1.793									1.522	720
				20.34	280.0	620.0	1.792									1.524	721
0.7060	0.0402	23.26	-11.0	33.6	2.330	1.898	863	0.7844	0.0408	22.47	176.5	233.1	1.599	1.290	1089		
				86.6	2.322	1.908	864										
				23.29	-11.4	183.6	2.222									1.840	865
				23.30	-11.6	383.9	2.117									1.777	866
				23.32	-11.8	483.4	2.060									1.735	867
0.7077	0.0563	14.67	276.0	333.2	1.291	1.027	687	0.7857	0.0254	36.12	176.0	233.1	2.018	1.678	1107		
				14.68	275.8	383.9	1.396									1.130	688
				14.69	275.5	483.4	1.466									1.207	689
				275.2	583.8	1.480	1.229									690	
				14.70	275.0	620.0	1.479									1.232	691
0.7091	0.0753	10.99	276.5	333.2	1.153	0.9013	656	0.7865	0.0249	40.63	-12.5	33.6	2.896	2.423	911		
				276.4	383.9	1.232	.9792									657	
				276.2	483.4	1.248	1.004									658	
				11.00	276.1	583.8	1.238									1.004	659
				276.0	620.0	1.228	.9981									660	
0.7127	0.0237	37.68	80.3	133.2	2.299	1.909	1017	0.7870	0.0570	17.70	-11.0	33.6	1.988	1.585	827		
				183.6	2.582	2.185	1018										
				283.2	3.611	2.234	1019										
				383.9	2.608	2.250	1020										
				483.4	2.899	2.542	1021										
0.7158	0.0408	21.99	82.0	133.2	1.987	1.621	510	0.7888	0.0733	13.09	78.5	133.2	1.454	1.133	462		
				183.6	2.145	1.778	511										
				283.2	2.036	1.698	512										
				383.9	1.997	1.677	513										
				483.4	1.957	1.652	514										
0.7240	0.0762	11.36	184.2	483.4	1.261	1.011	567	0.7899	0.0557	17.23	80.0	133.2	1.672	1.331	480		
				583.8	1.246	1.006	568										
				11.35	185.0	620.1	1.242									1.005	569
				11.35	185.0	620.1	1.242									1.005	569
				12.17	77.0	133.2	1.470									1.147	456
0.7373	0.0754	12.17	77.0	133.2	1.470	1.147	456	0.7928	0.0401	24.00	81.0	133.2	2.039	1.669	516		
				183.6	1.477	1.163	457										
				283.2	1.442	1.146	458										
				383.9	1.414	1.133	459										
				483.4	1.366	1.099	460										
0.7582	0.0141	69.57	-8.5	33.6	3.786	3.353	972	0.7944	0.0734	13.78	-6.0	33.6	1.854	1.464	785		
				86.6	3.849	3.334	973										
				183.6	3.796	3.317	974										
				383.9	3.685	3.261	975										
				483.4	3.636	3.233	976										

TABLE II. - ORGANIZATION OF RESULTS FOR NOMINAL VALUES OF PARAMETERS

Nominal Knudsen number, Kn	Nominal Mach number, M								
	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
Run numbers ^a for $T_t \approx 0^\circ \text{ F}$									
0.0770	342 420	336 414	330 408	402	767	773	761	779	785
0.0555	396	390	324 384	815	809	791 803	797	821	827
0.0416	378	372	857	839	833	845 869	851	863	875
0.0256	354 360	366	917	887	881	893	899 905	---	911
0.0143	348	935	923	929	941	959	965	---	972
0.00916	---	984	947	953 978	990	995	---	---	---
Run numbers ^a for $T_t \approx 80^\circ \text{ F}$									
0.0770	1	13 37	25 49	61	73 426	432	438	456	462
0.0555	85	91	97	103	444	450	468	474	480
0.0416	109	115 127	121 262	486	492	498	504	510	516
0.0256	133	139 522	528	534	540	546	1005	1011 1017	---
0.0143	145	1035	1029	1023	1041	1047	1083	----	---
0.00916	151	1065	1053	1059	1071	1077	----	----	---
Run numbers ^a for $T_t \approx 180^\circ \text{ F}$									
0.0770	169	163	157	175	---	---	---	567	575
0.0555	193	181	187	199	552 599	558 581	587	593	605
0.0416	217	211	205	611	617	623	630	635	1089
0.0256	223	229	743	737	749	755	1095	1101	1107
0.0143	235	---	---	---	1113	1119	----	----	----
Run numbers ^a for $T_t \approx 280^\circ \text{ F}$									
0.0770	278	247	252	257	646	---	651	656	661
0.0555	283	273	268	671	666	641 676	681	687	692
0.0416	288	293 299	304	697	702	707	712	717	---
0.0256	309	314	722	727	732	---	---	---	---
0.0143	319	---	---	---	---	---	---	---	---

^aEach run number is the first of a group of runs in table I at the indicated nominal values of M, Kn, and T_t .

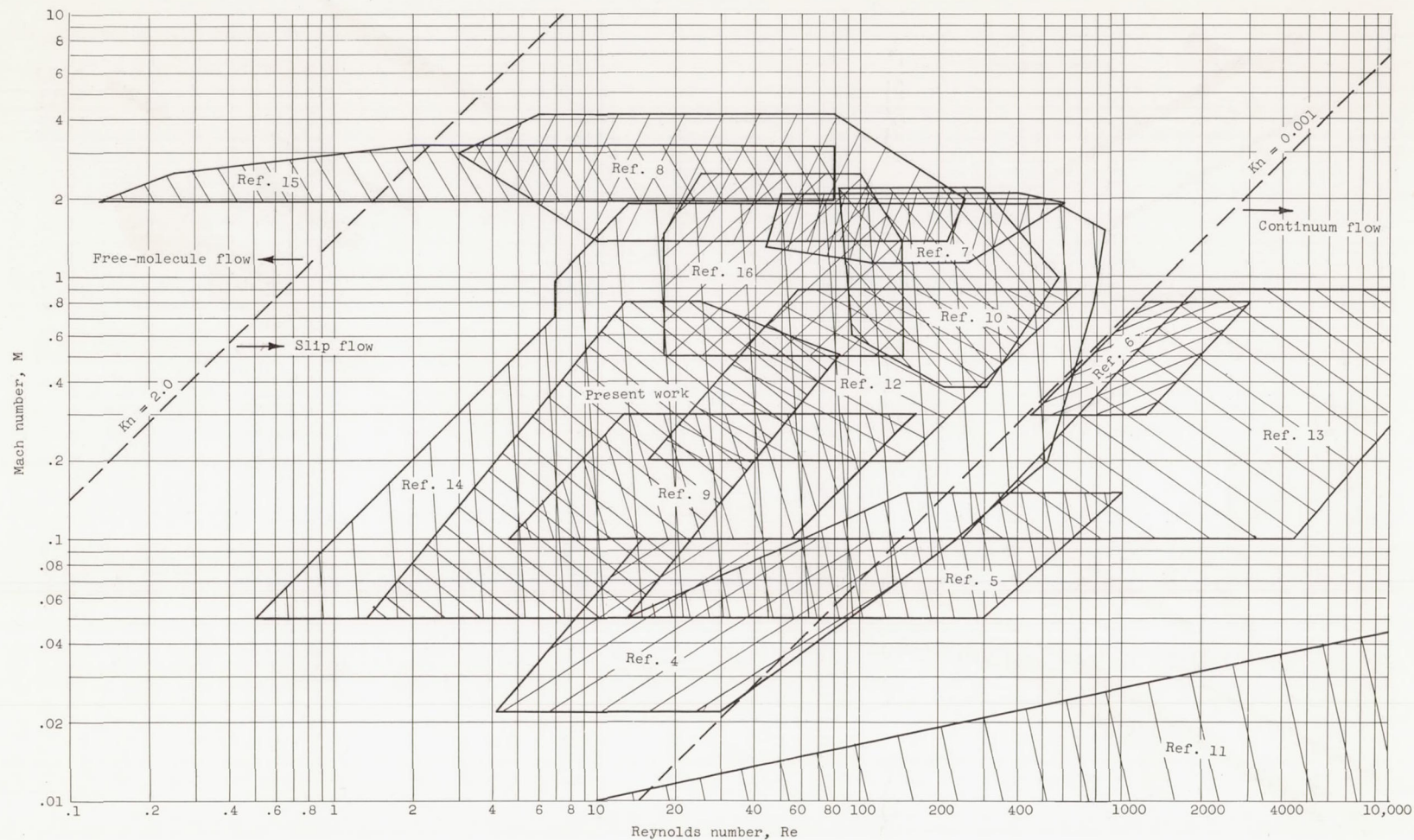


Figure 1. - Comparison of Mach and Reynolds number ranges of heat-transfer experiments with normal cylinders. Flow regions after reference 15.

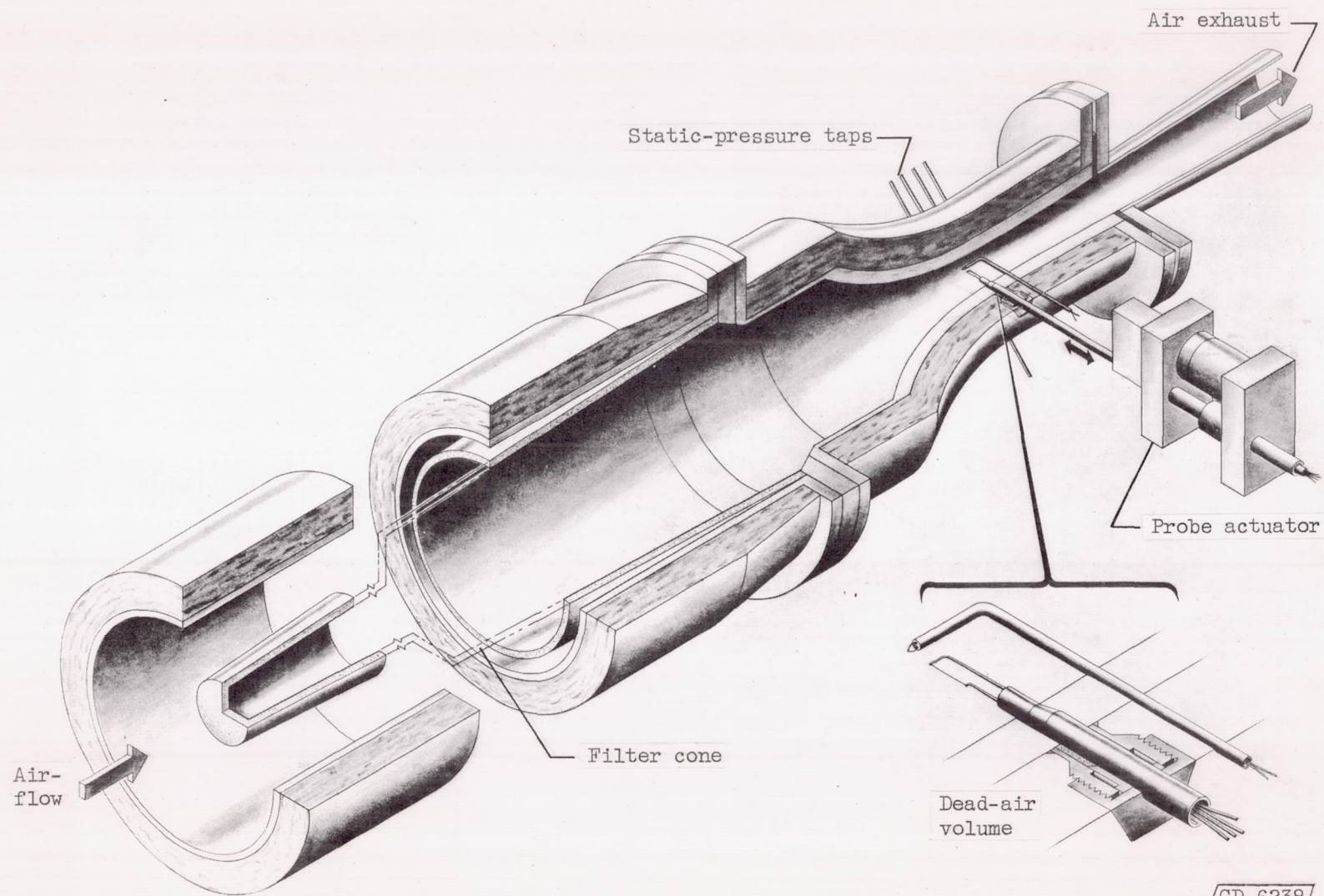


Figure 2. - Variable-density subsonic tunnel.

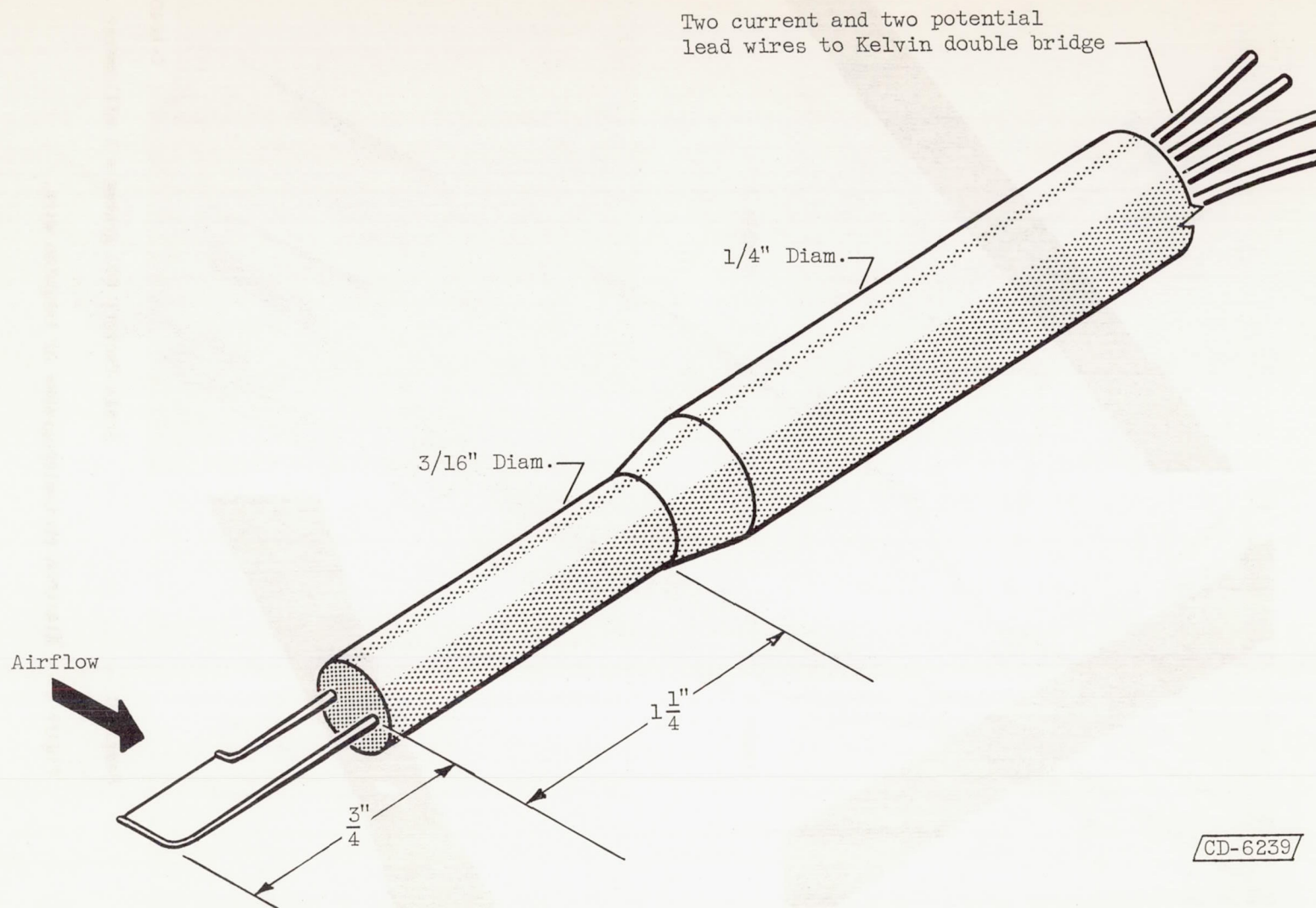
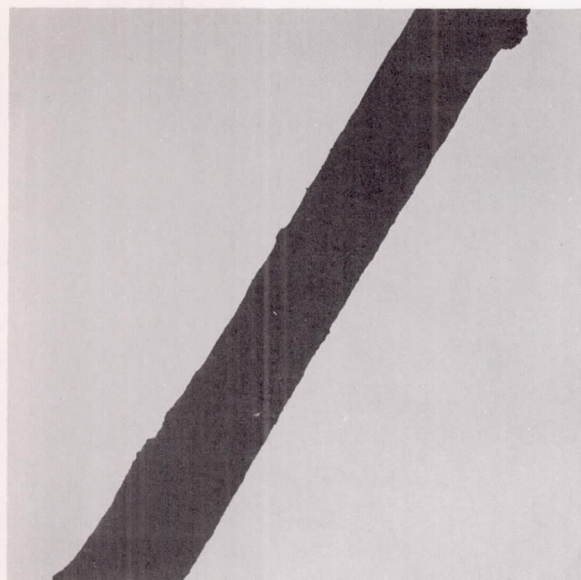
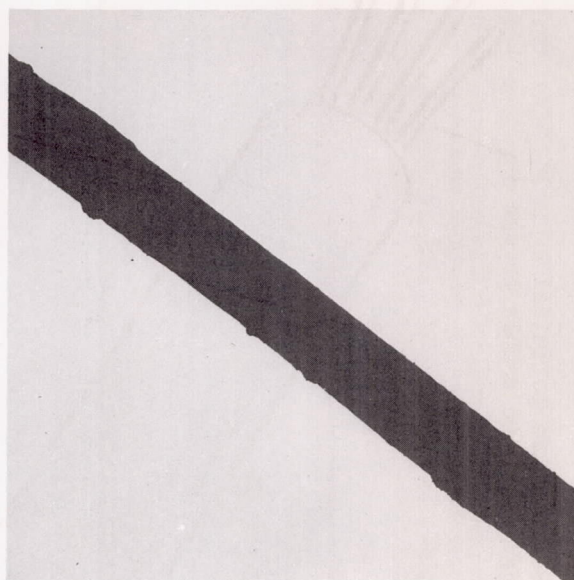


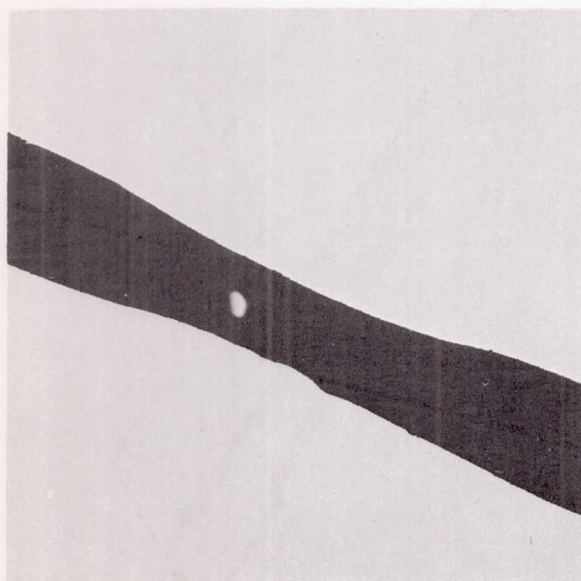
Figure 3. - Tungsten-wire supporting probe.



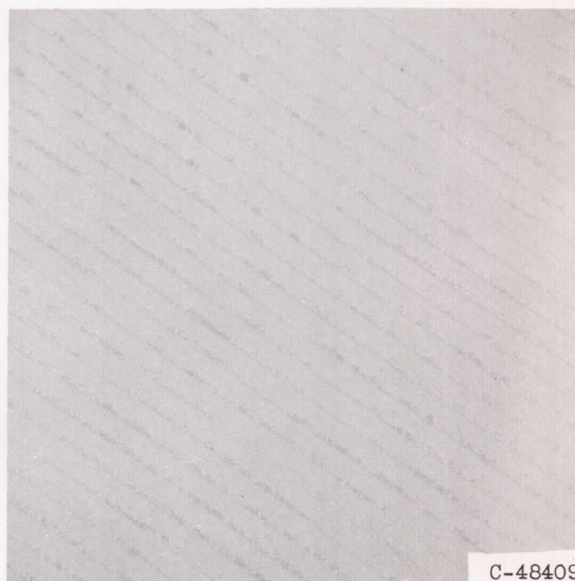
Sample A



Sample B



Sample C



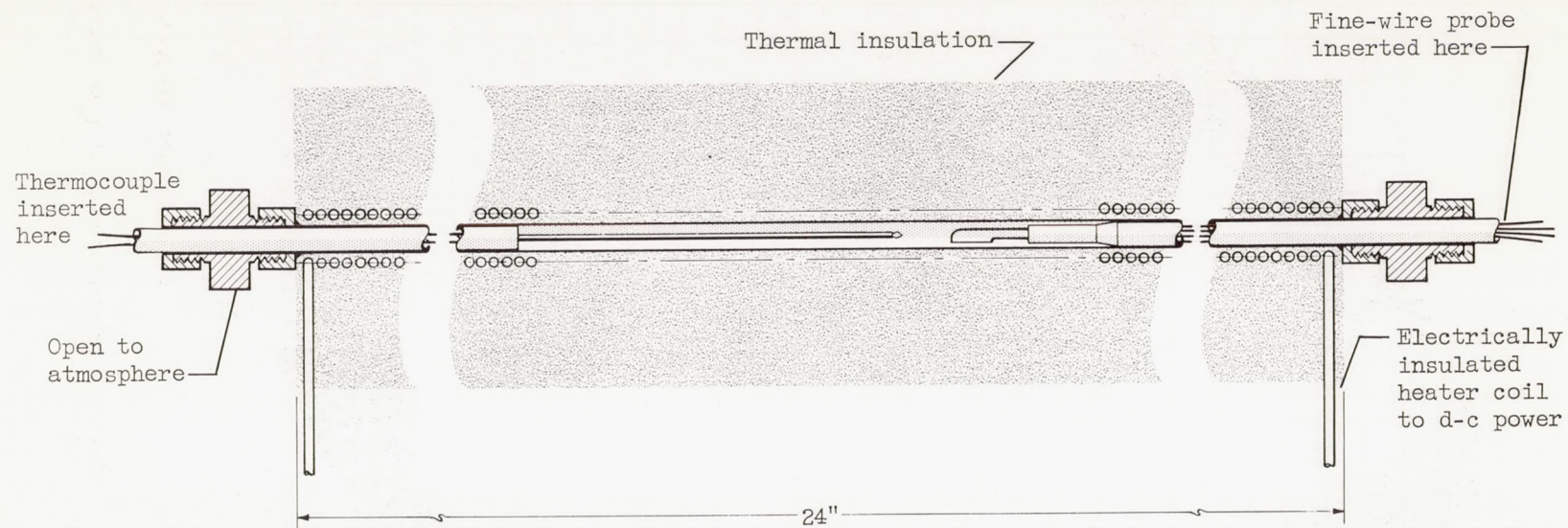
C-48409

Scale factor; 600 grates = 1 millimeter

Figure 4. - Electron photomicrographs of tungsten wire.

5111

CS-7 back



CD-6240

Figure 5. - Resistance-temperature calibration tank.

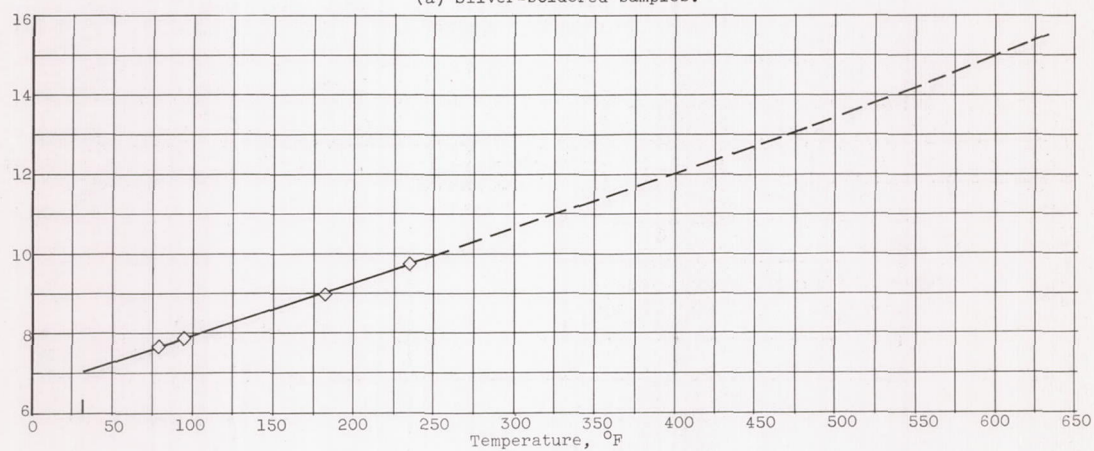
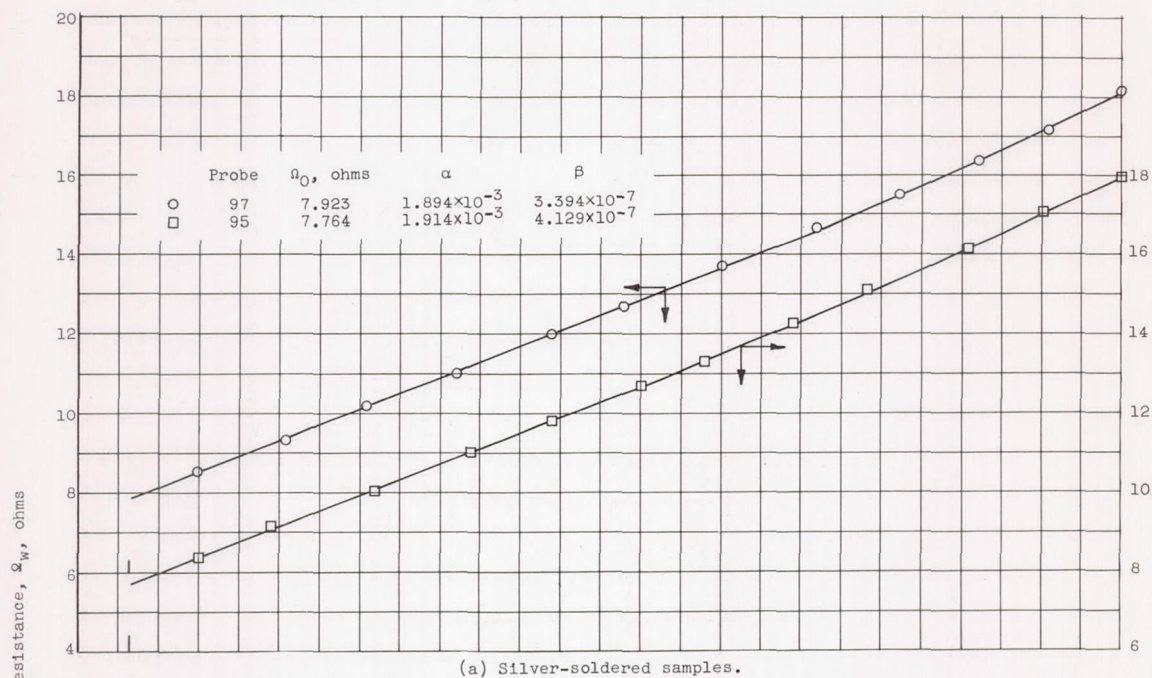
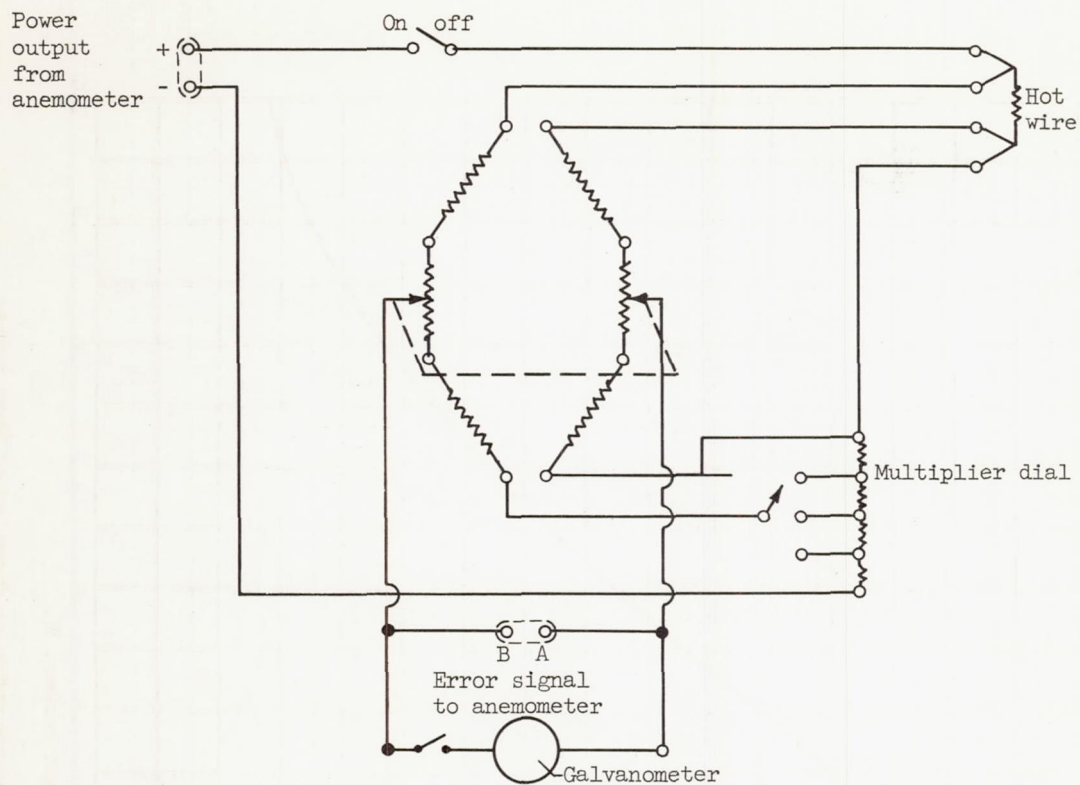
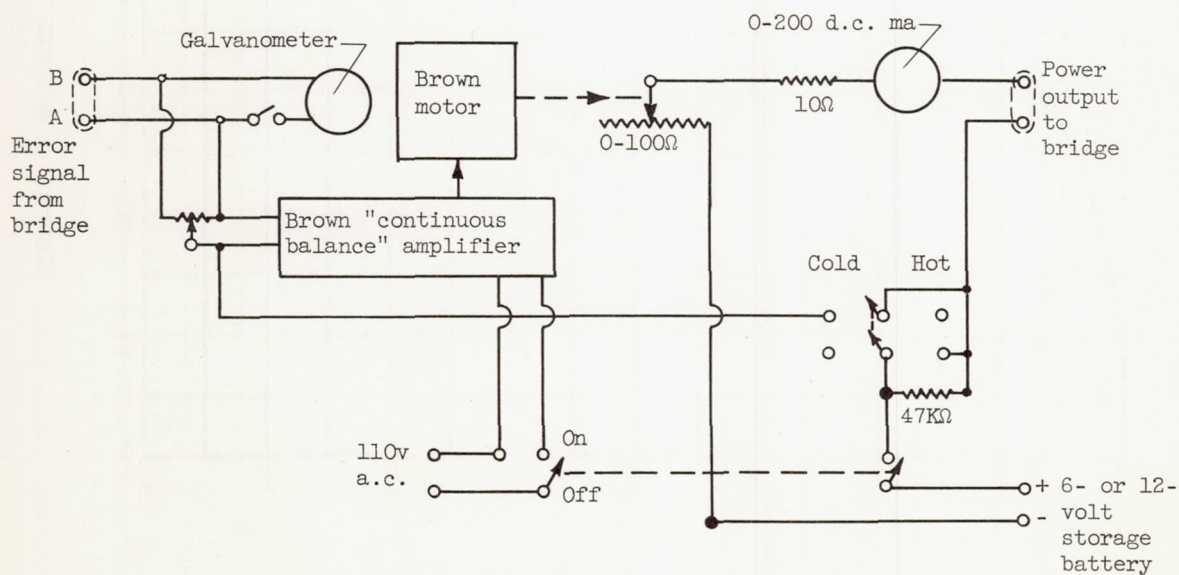


Figure 6. - Calibration of wire electrical resistance and temperature.



(a) Kelvin bridge ohmmeter.



(b) Constant-average-temperature anemometer.

Figure 7. - Anemometer electrical equipment.

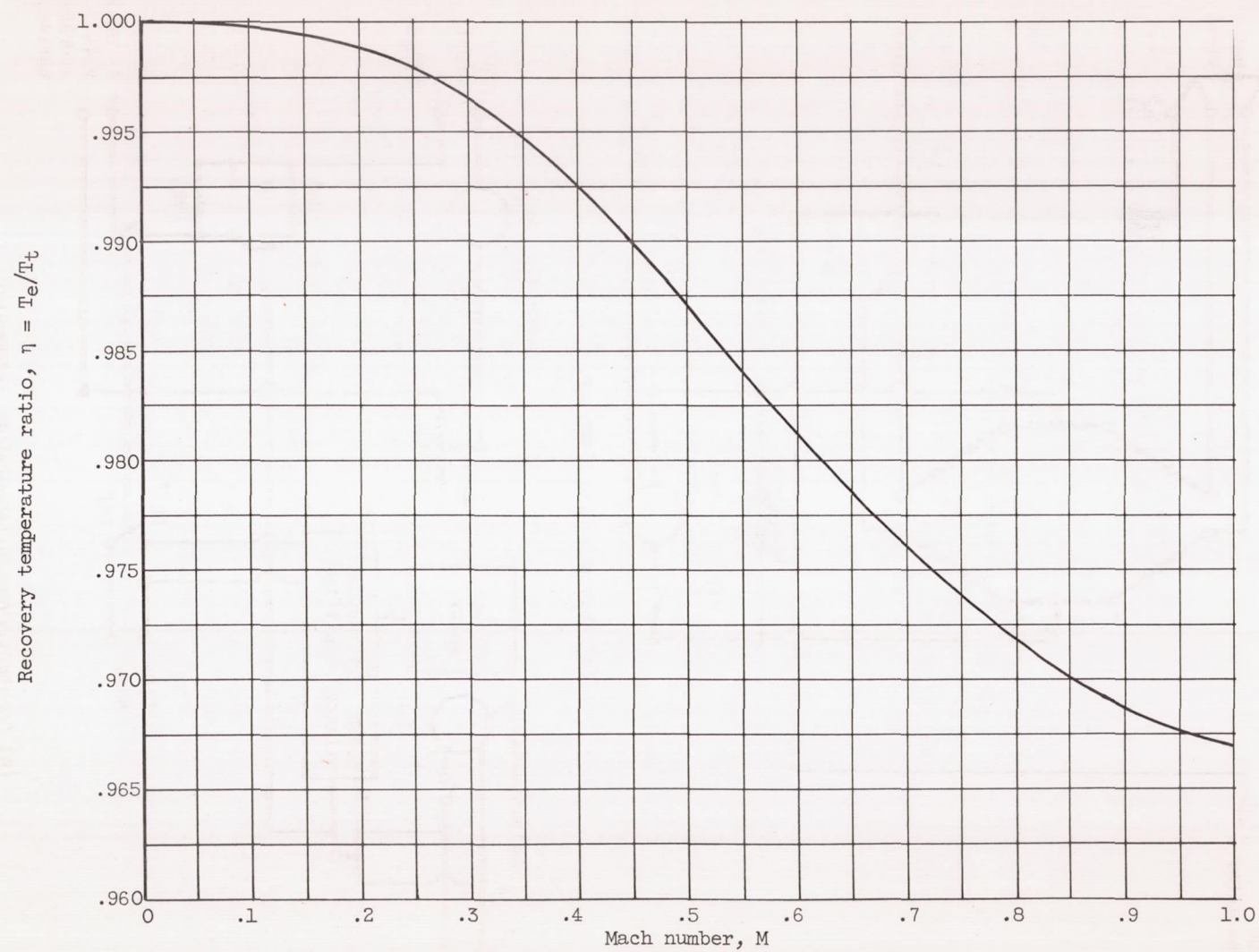


Figure 8. - Recovery temperature ratio as function of Mach number.

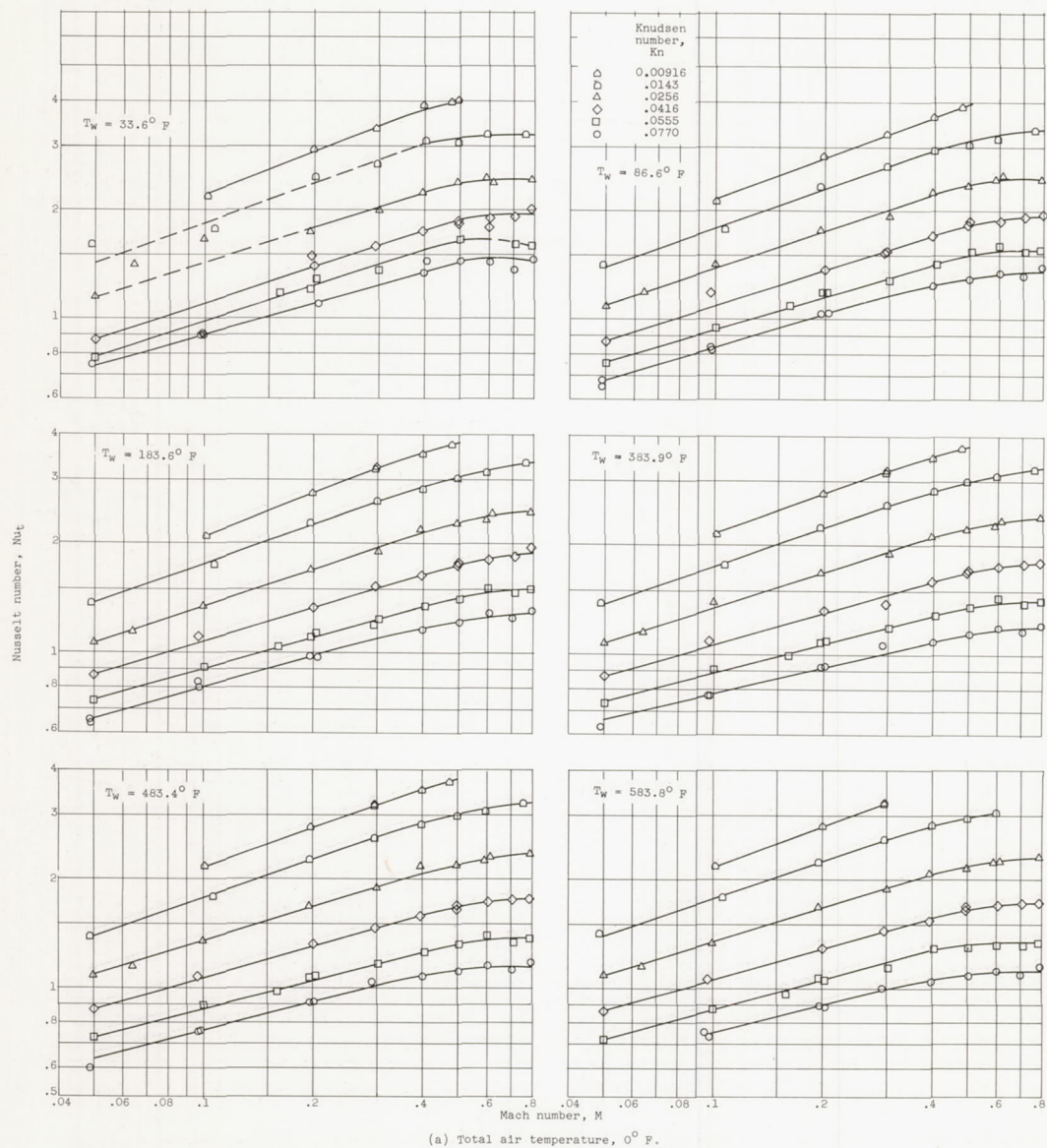
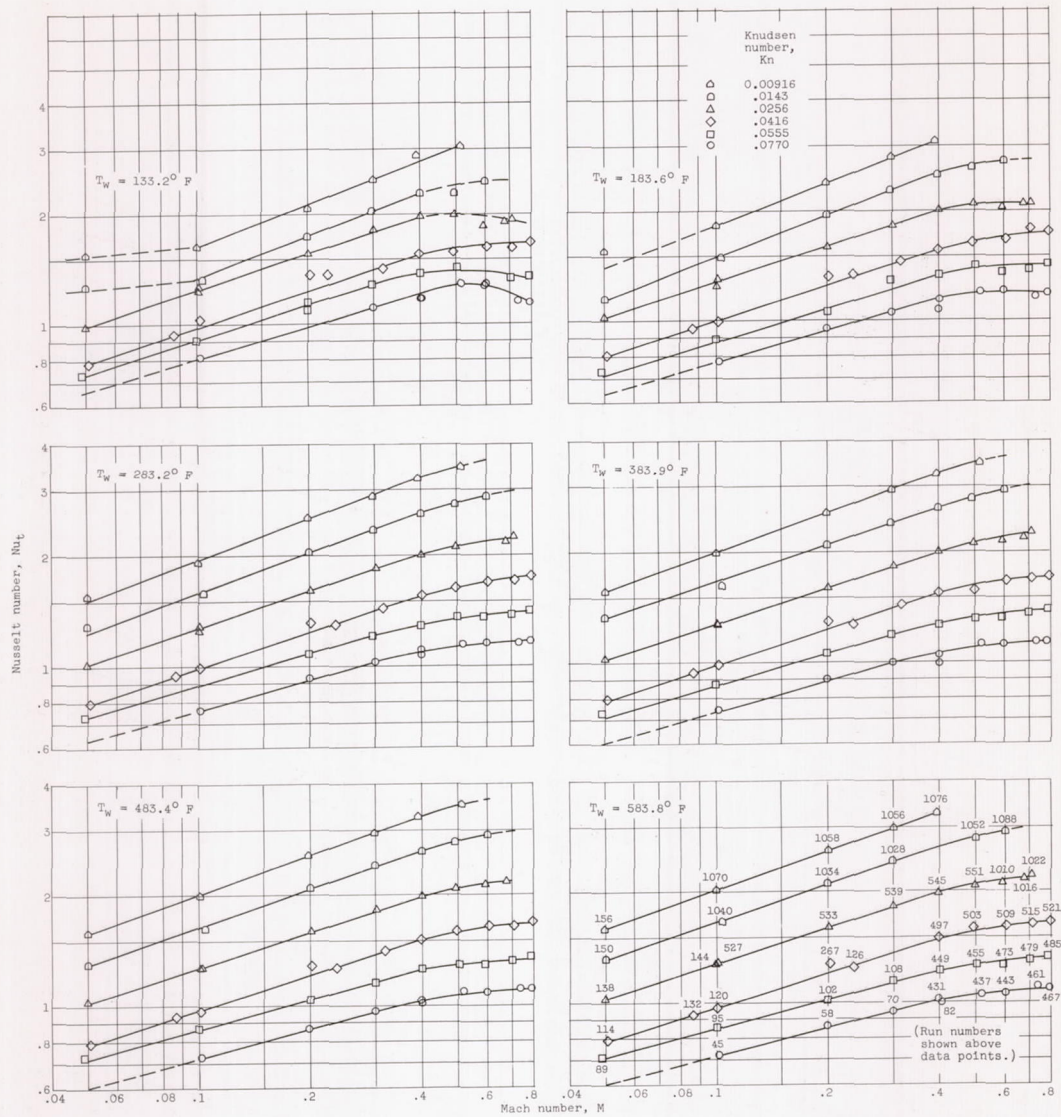


Figure 9. - Variation of Nusselt number with Mach number for constant Knudsen number and constant total air and cylinder temperatures.



(b) Total air temperature, 80° F.

Figure 9. - Continued. Variation of Nusselt number with Mach number for constant Knudsen number and constant total air and cylinder temperatures.

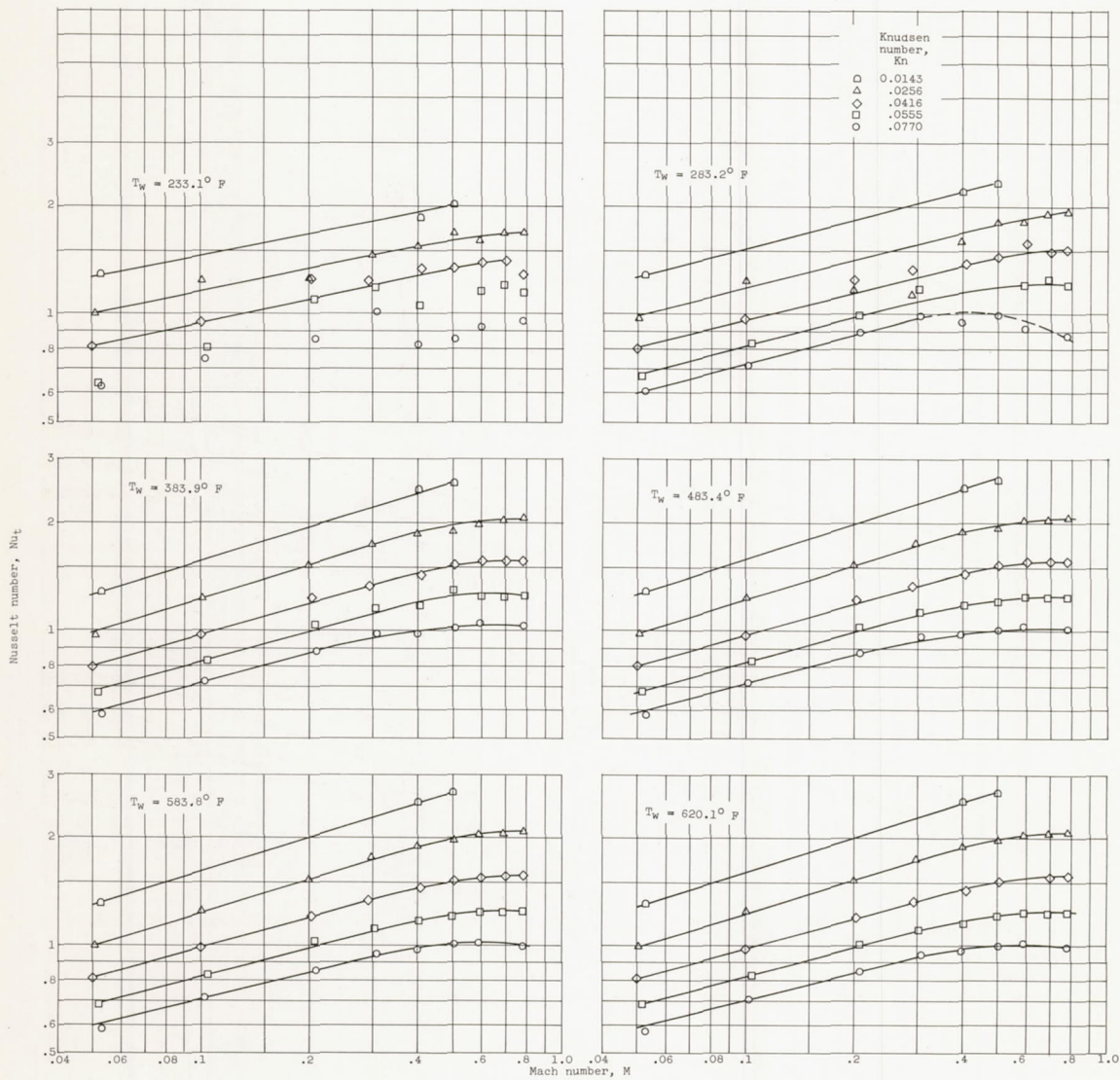
(c) Total air temperature, 180° F .

Figure 9. - Continued. Variation of Nusselt number with Mach number for constant Knudsen number and constant total air and cylinder temperatures.

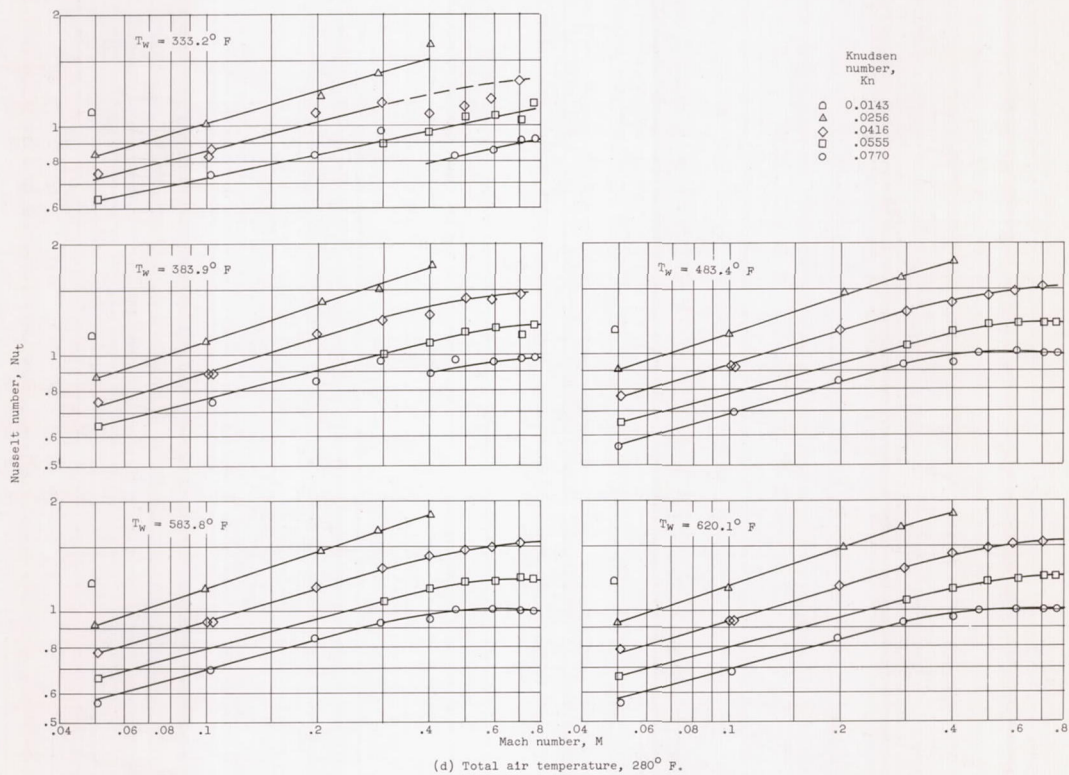


Figure 9. - Concluded. Variation of Nusselt number with Mach number for constant Knudsen number and constant total air and cylinder temperatures.

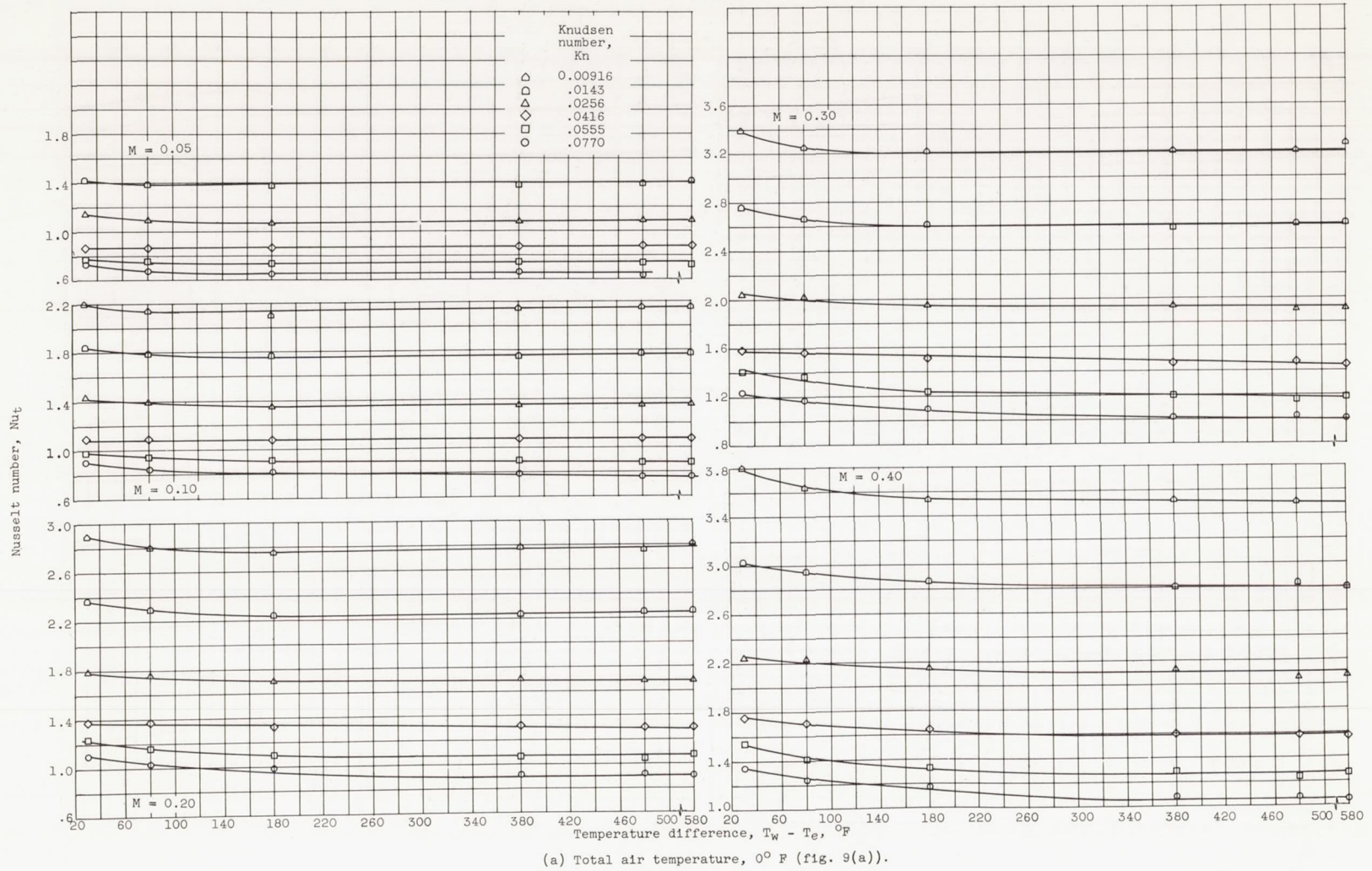
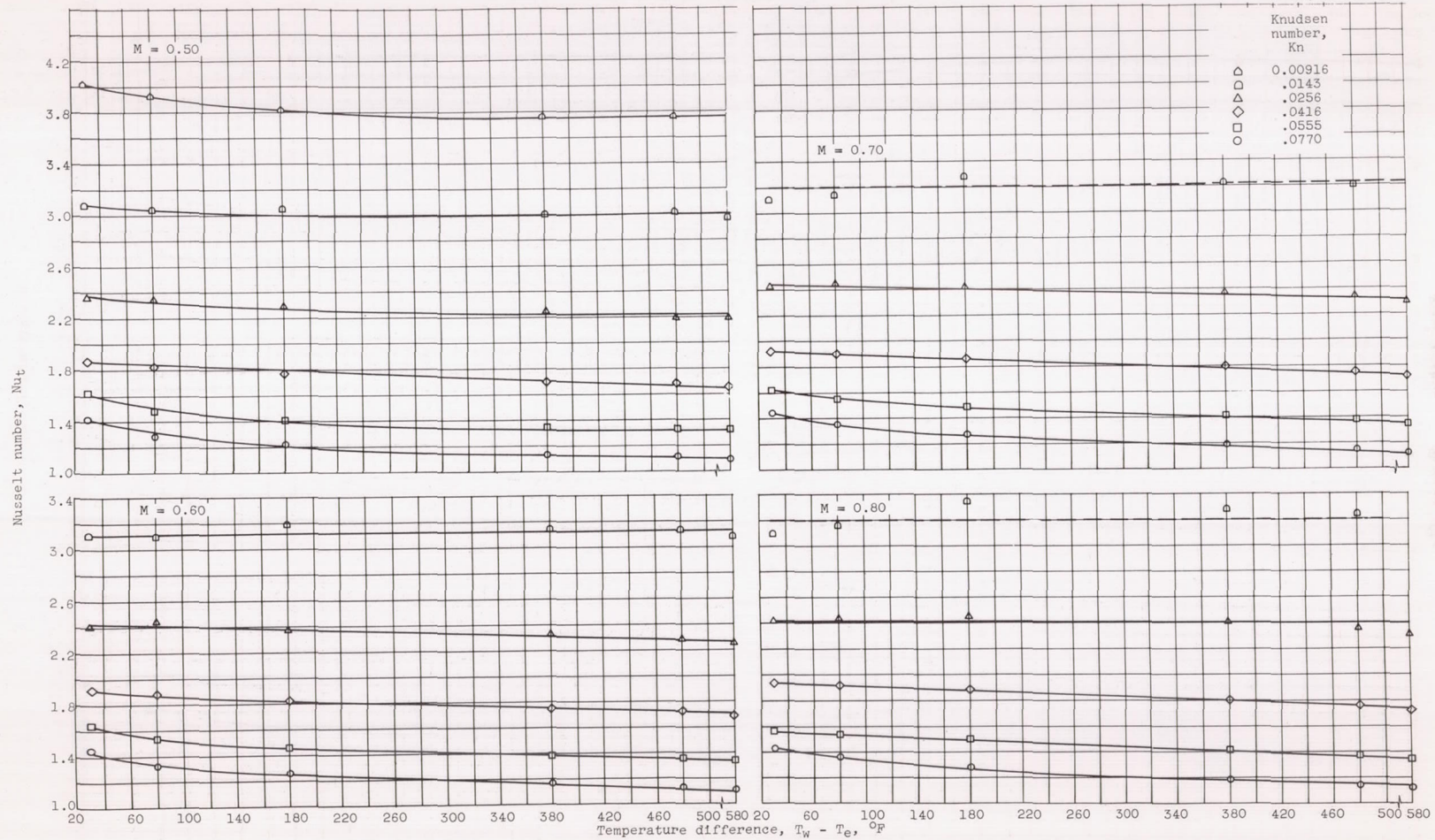
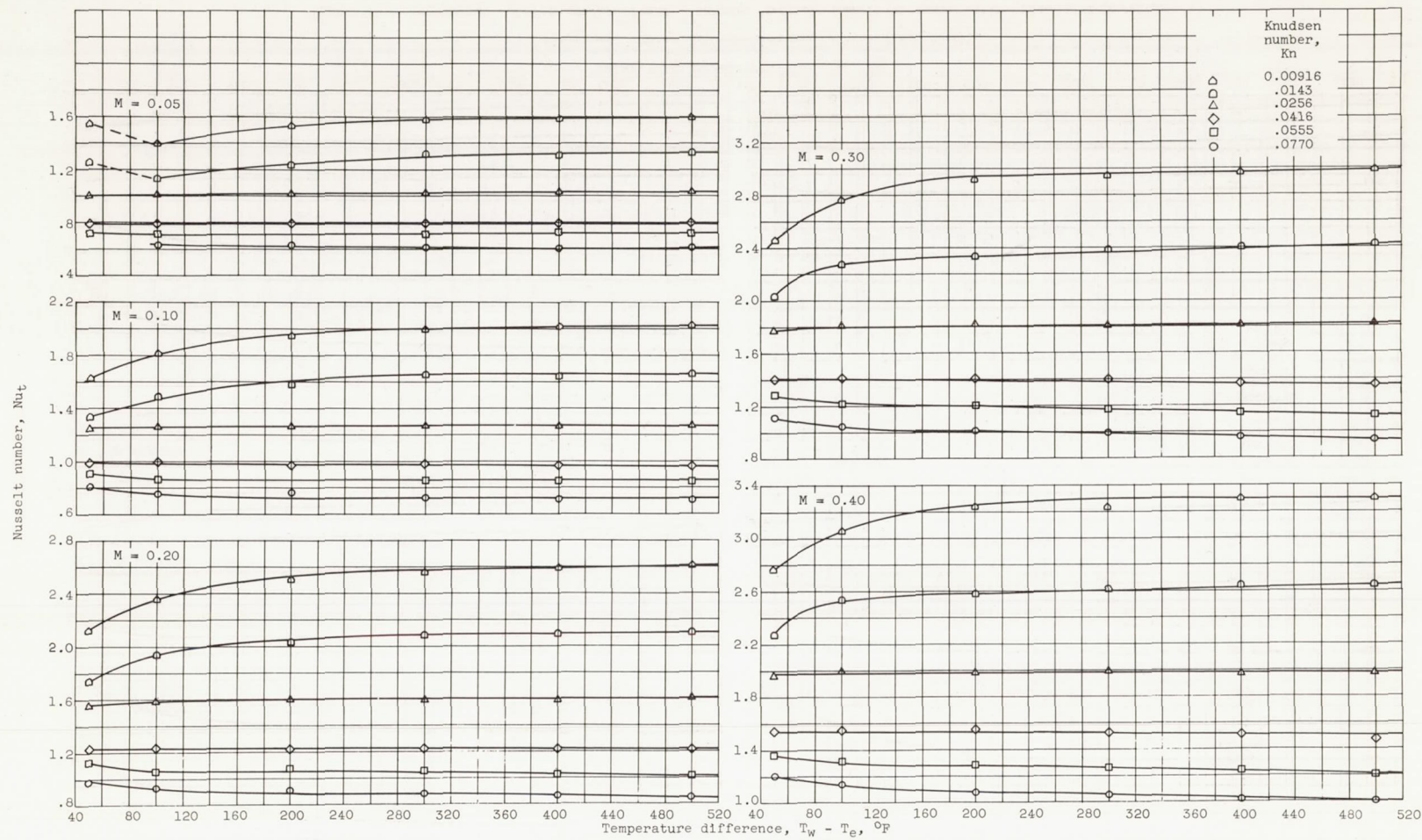


Figure 10. - Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.



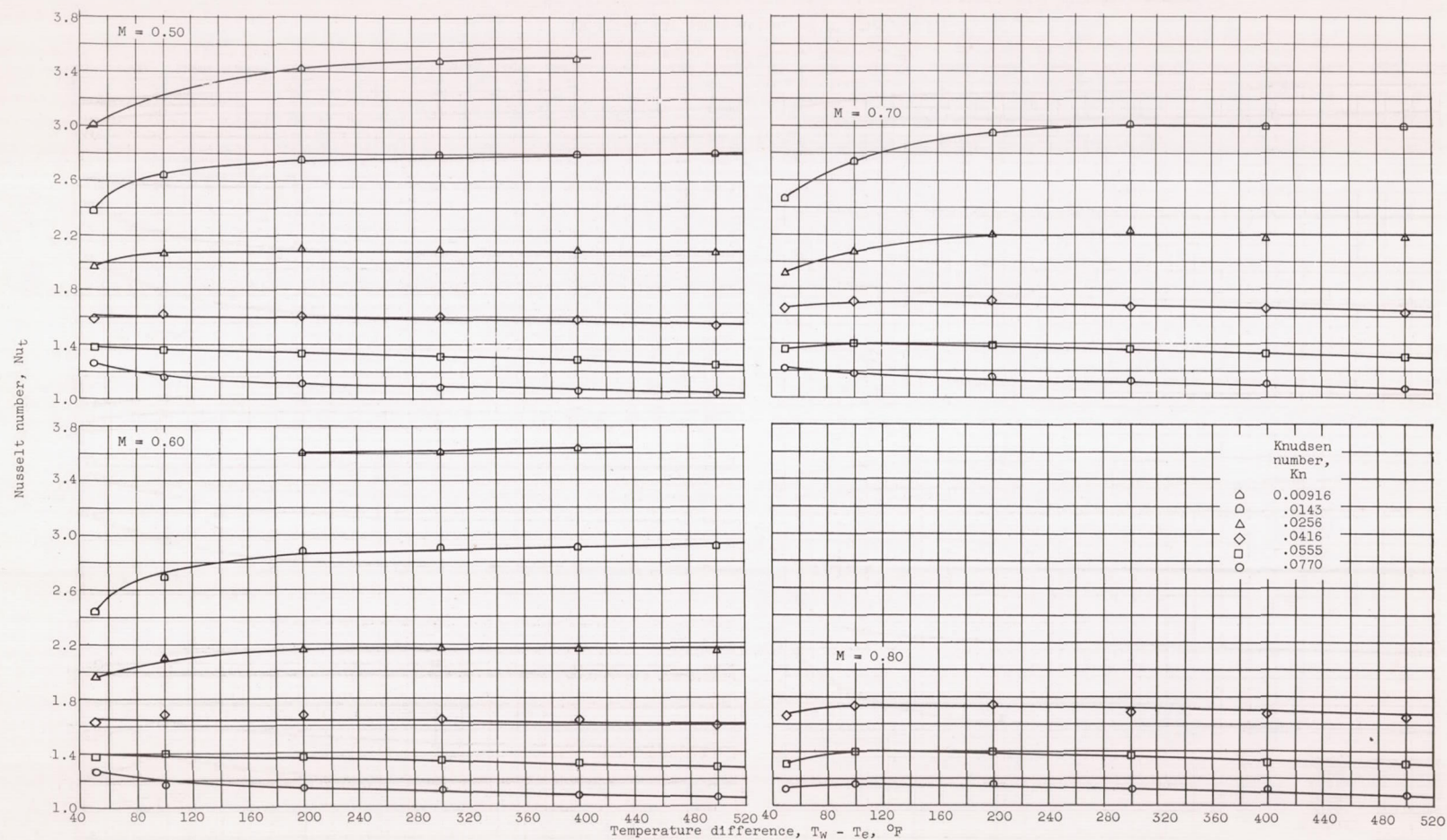
(a) Concluded. Total air temperature, $^{\circ}\text{F}$ (fig. 9(a)).

Figure 10. - Continued. Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.



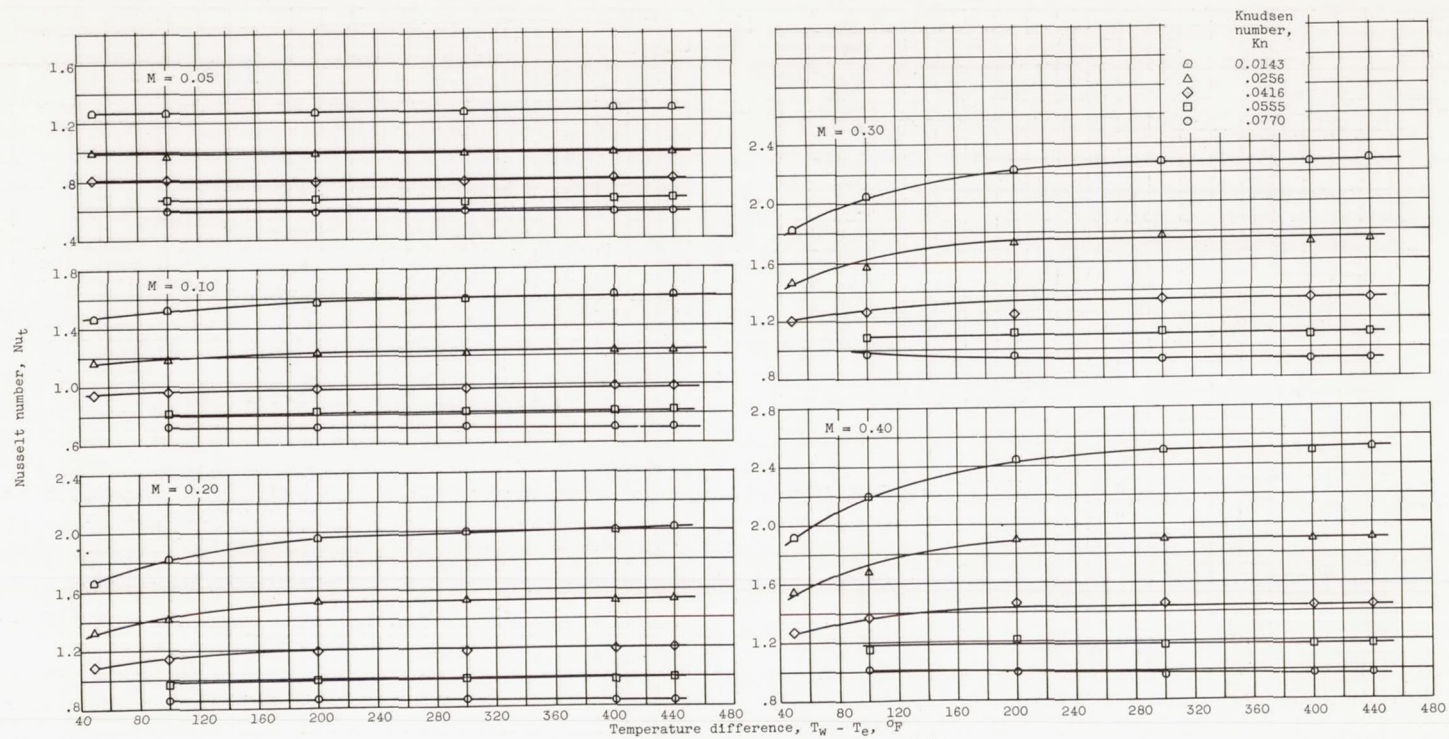
(b) Total air temperature, 80°F (fig. 9(b)).

Figure 10. - Continued. Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.



(b) Concluded. Total air temperature, 80°F (fig. 9(b)).

Figure 10. - Continued. Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.



(c) Total air temperature, $180^{\circ}F$ (fig. 9(c)).

Figure 10. - Continued. Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.

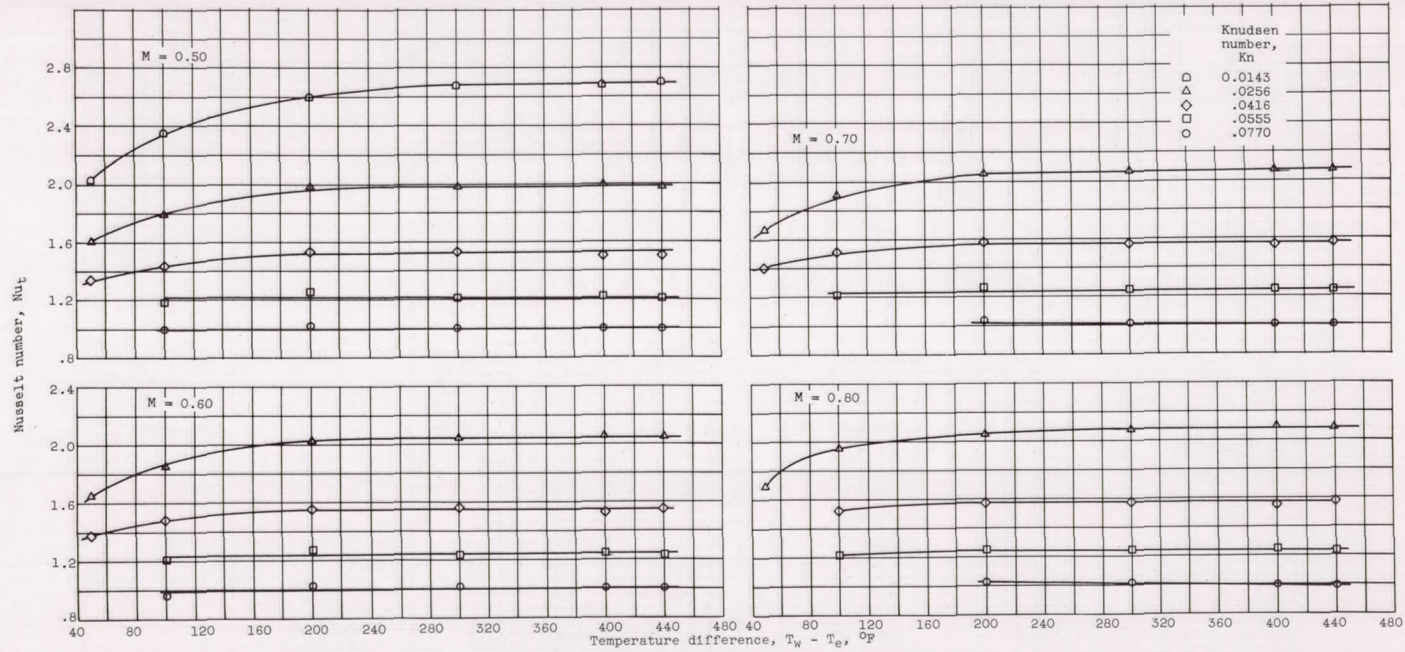
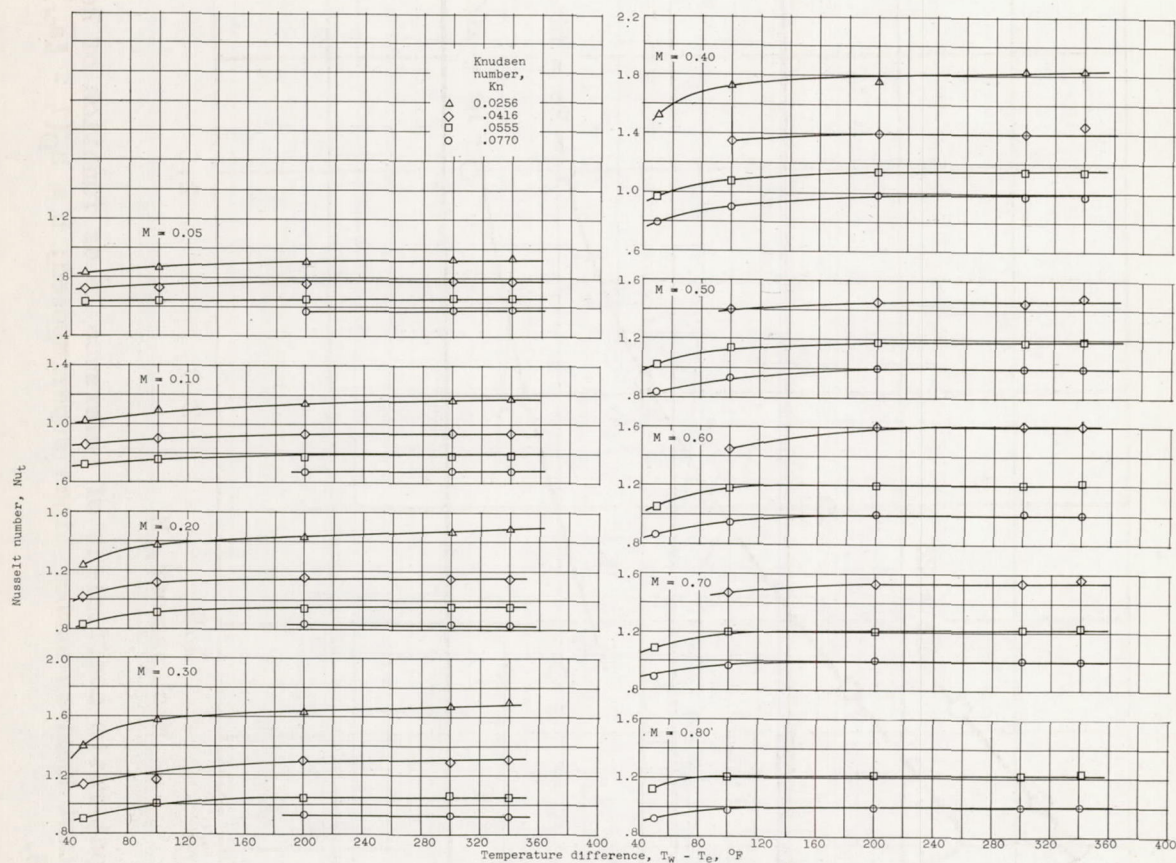


Figure 10. - Continued. Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.



(d) Total air temperature, 280°F (fig. 9(d)).

Figure 10. - Concluded. Crossplots of figure 9 showing Nusselt number variation with cylinder temperature.

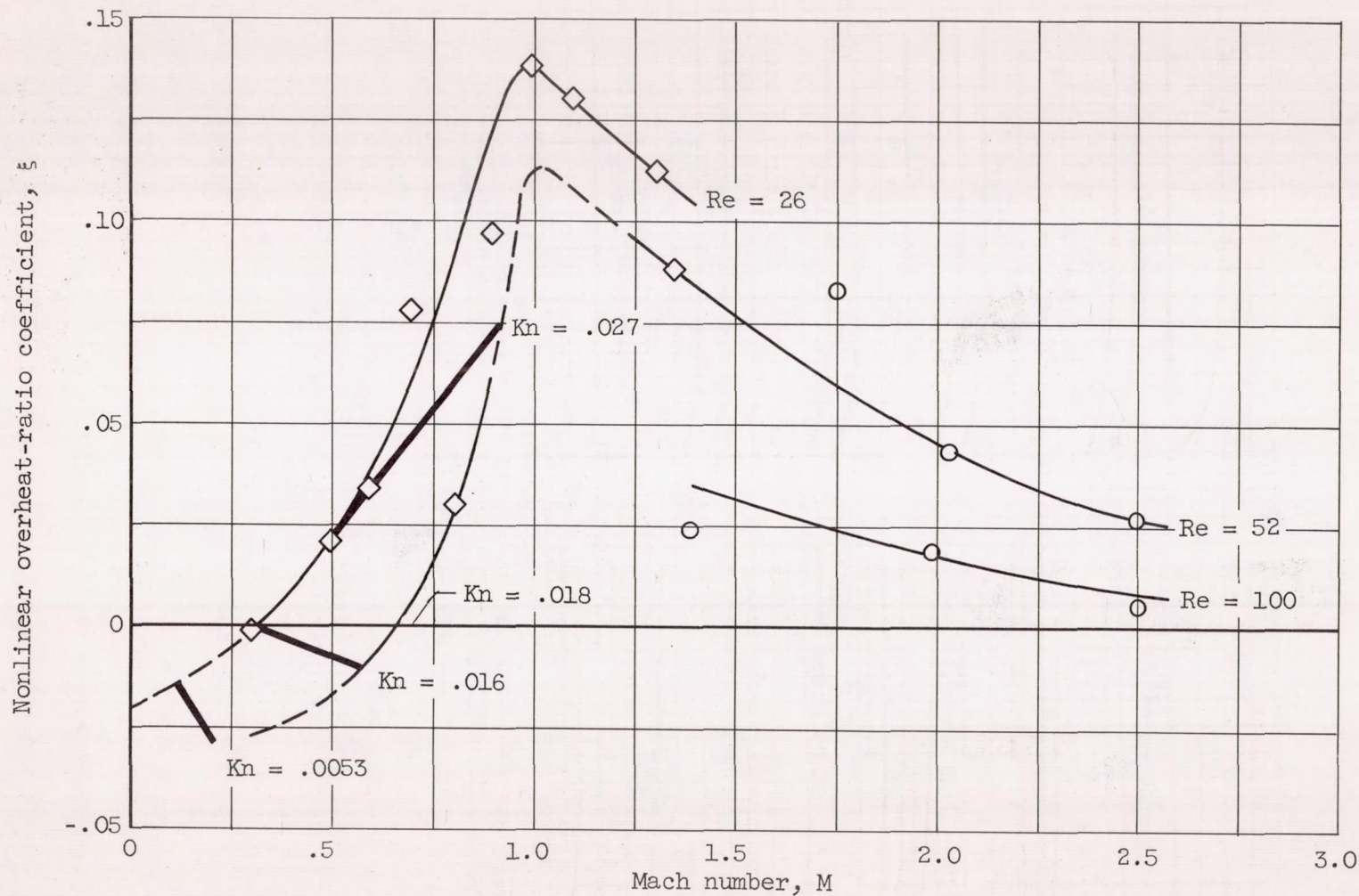


Figure 11. - Nonlinear overheat-ratio coefficient of reference 16 as function of Reynolds and Mach numbers with constant Knudsen number lines superimposed; $h = h_0(1 - \xi a_w)$. Data points of reference 16.

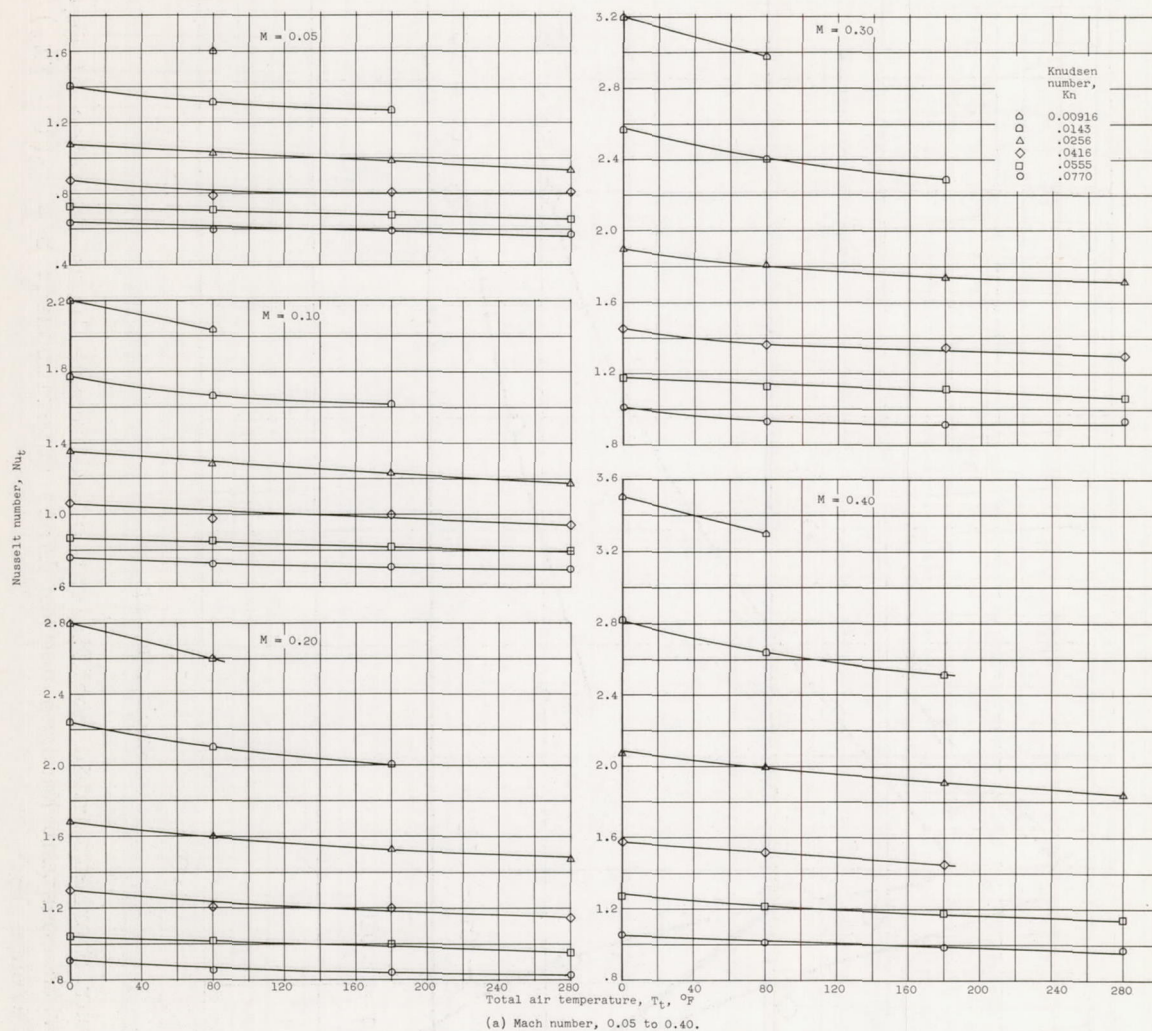


Figure 12. - Variation of Nusselt number with total air temperature. Crossplots of figure 10 showing asymptotic Nusselt number at $\Delta T > 200^{\circ} F$.

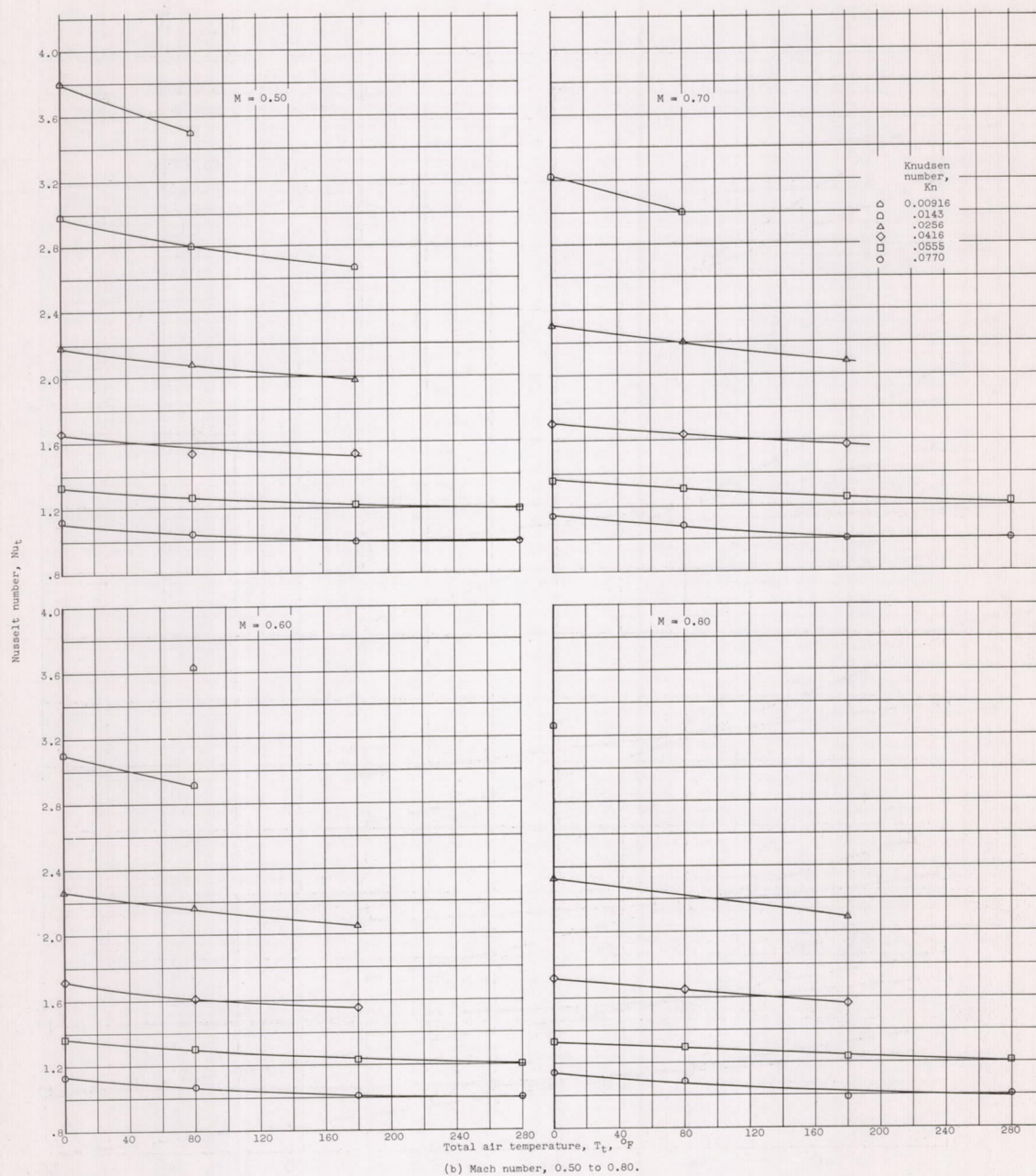


Figure 12. - Concluded. Variation of Nusselt number with total air temperature. Crossplots of figure 10 showing asymptotic Nusselt number at $\Delta T > 200^\circ \text{F}$.

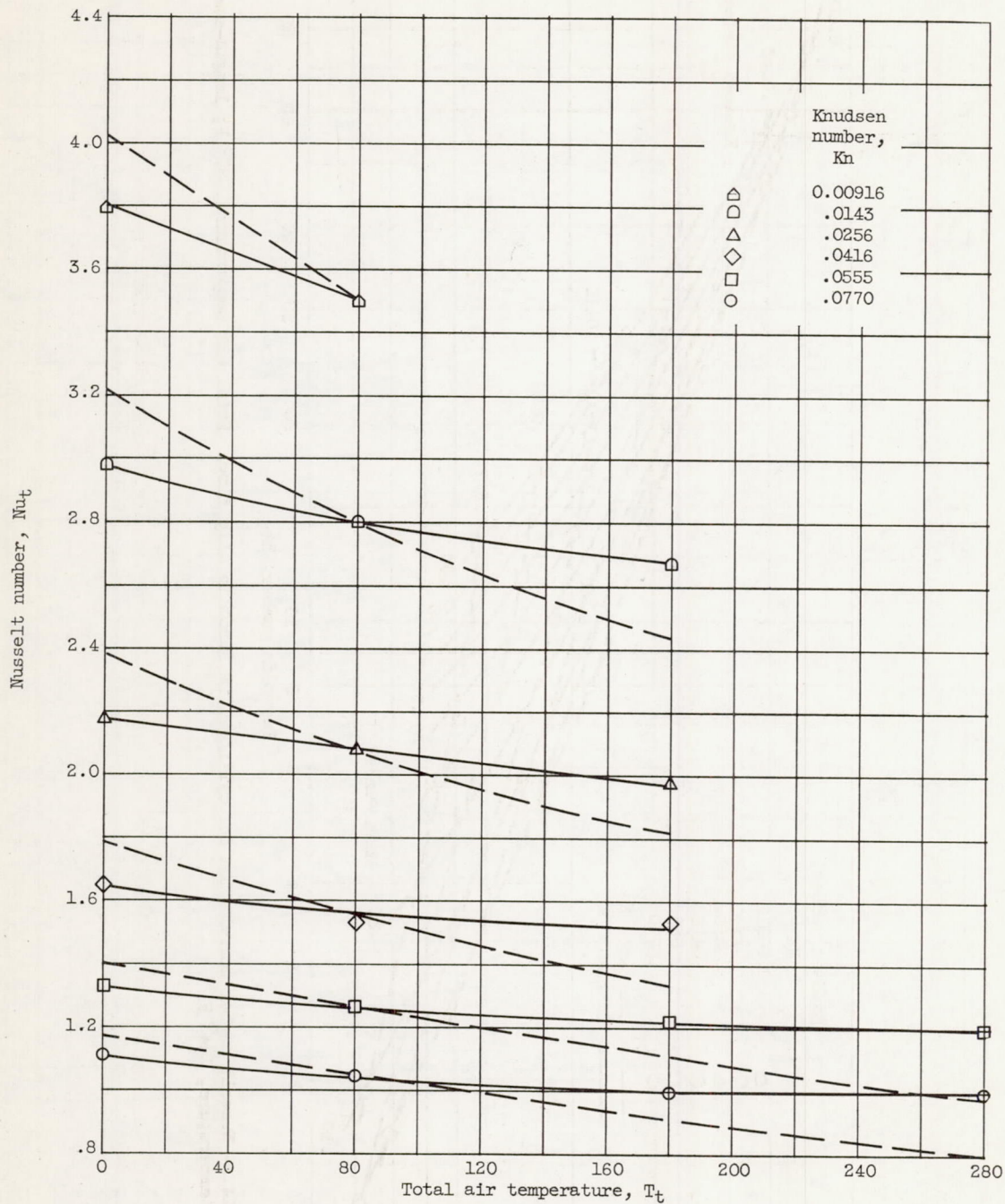


Figure 13. - Variation of Nusselt number with total air temperature. Curves of constant heat-transfer coefficient h_{0F} superimposed on figure 12(b) for $M = 0.50$.

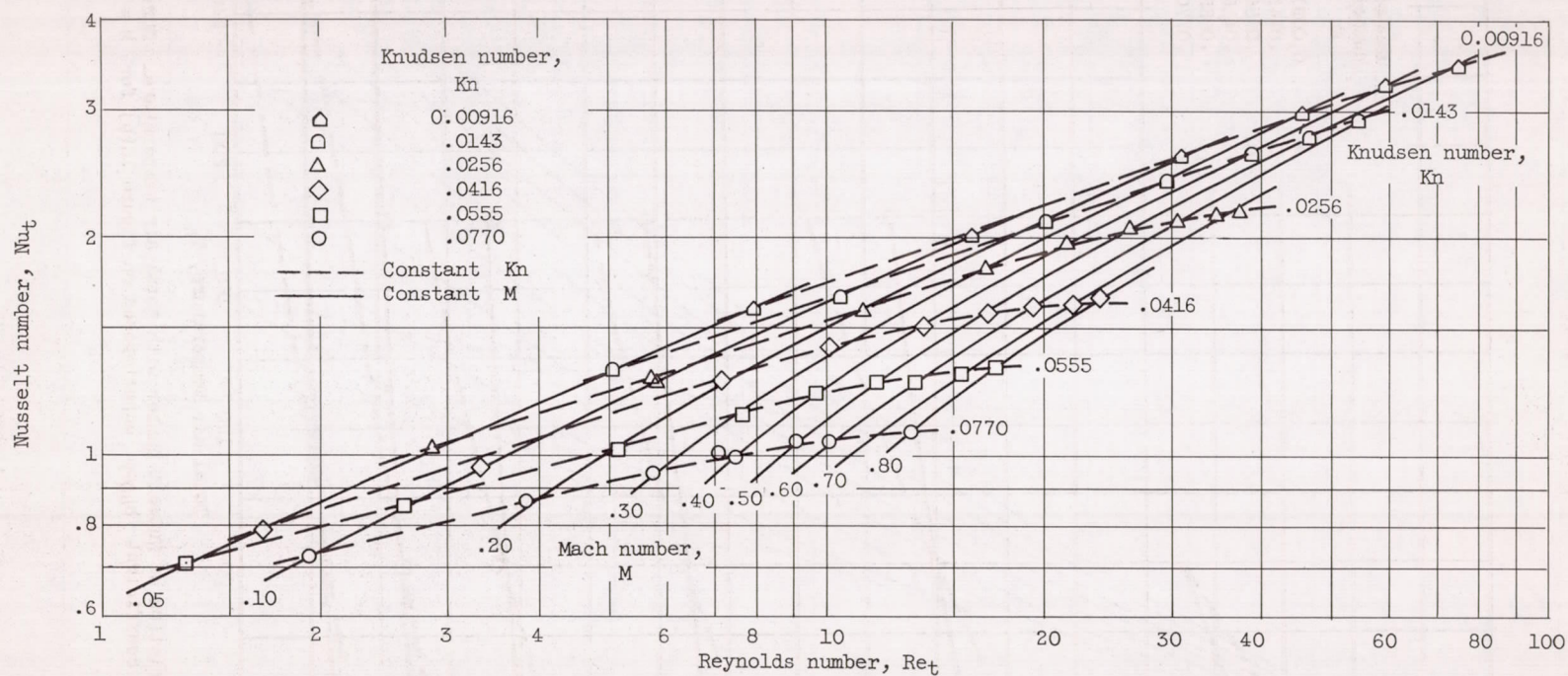


Figure 14. - Nusselt number correlation for cylinders in subsonic slip flow. Total air temperature, 80°F ; length-average wire temperature, 584°F .

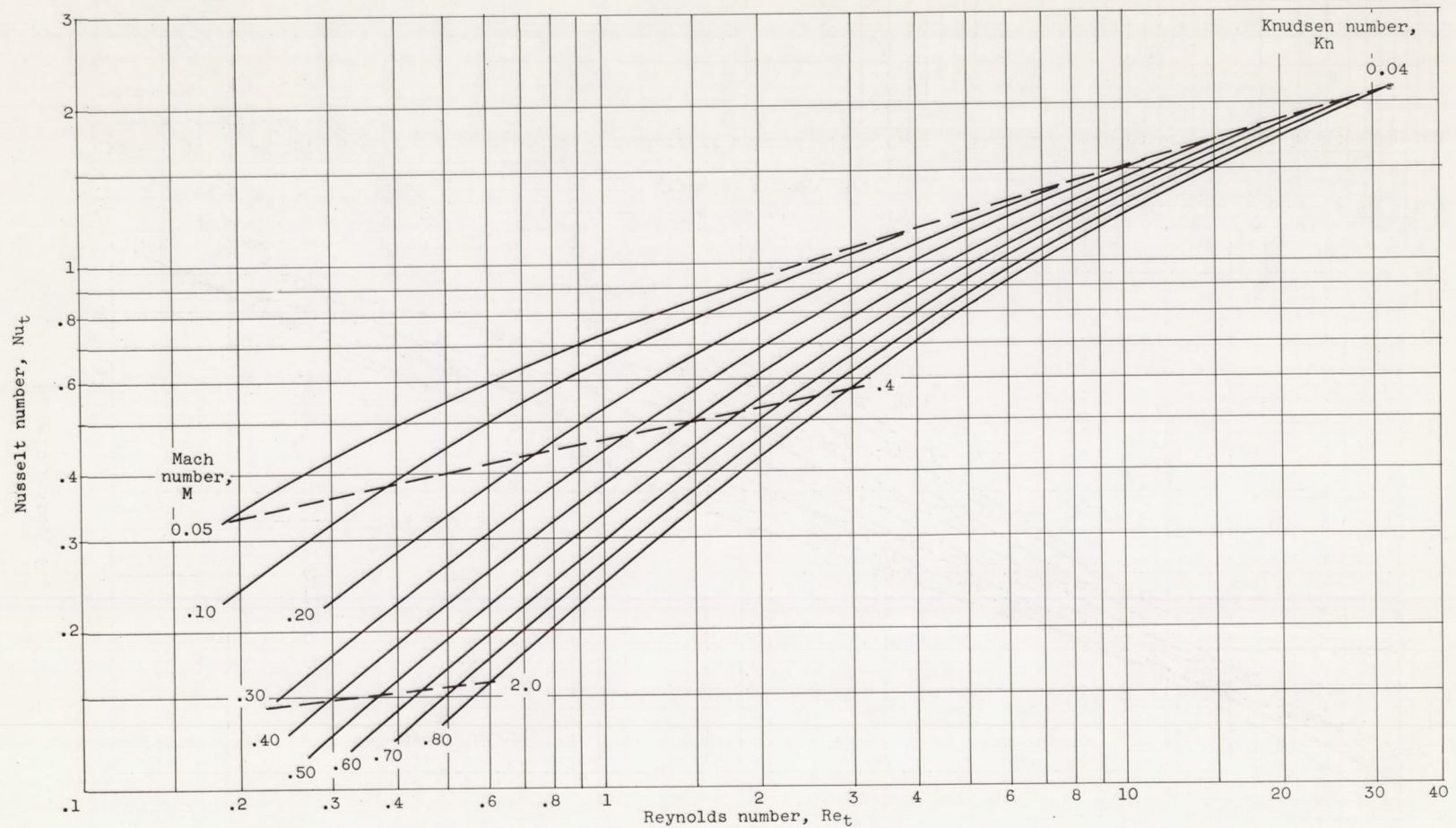


Figure 15. - Predicted Nusselt number correlation from approximate slip-flow theory (after ref. 23).

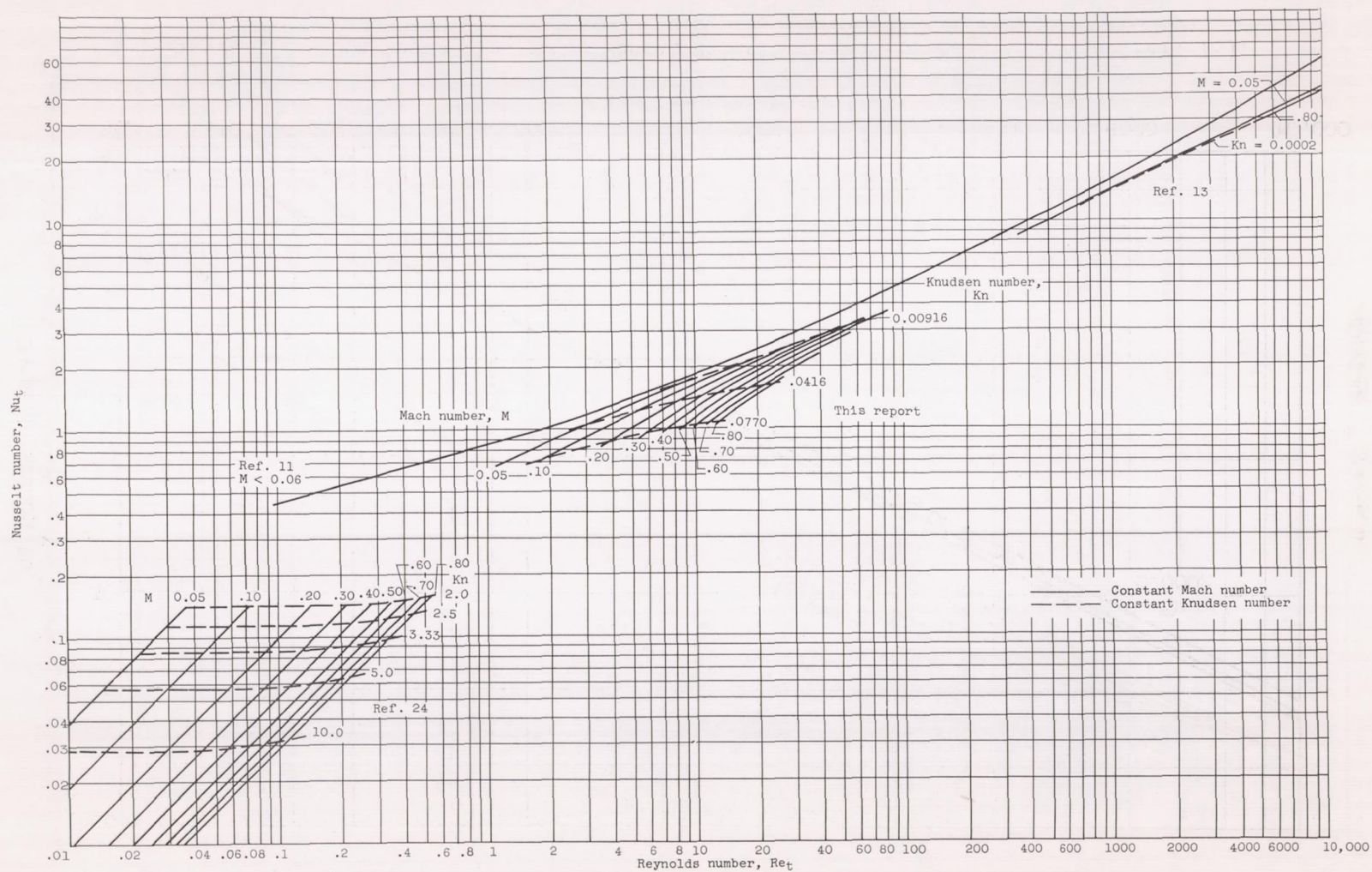


Figure 16. - Attempted Nusselt number correlation for cylinders in subsonic continuum, slip, and free-molecule flows.

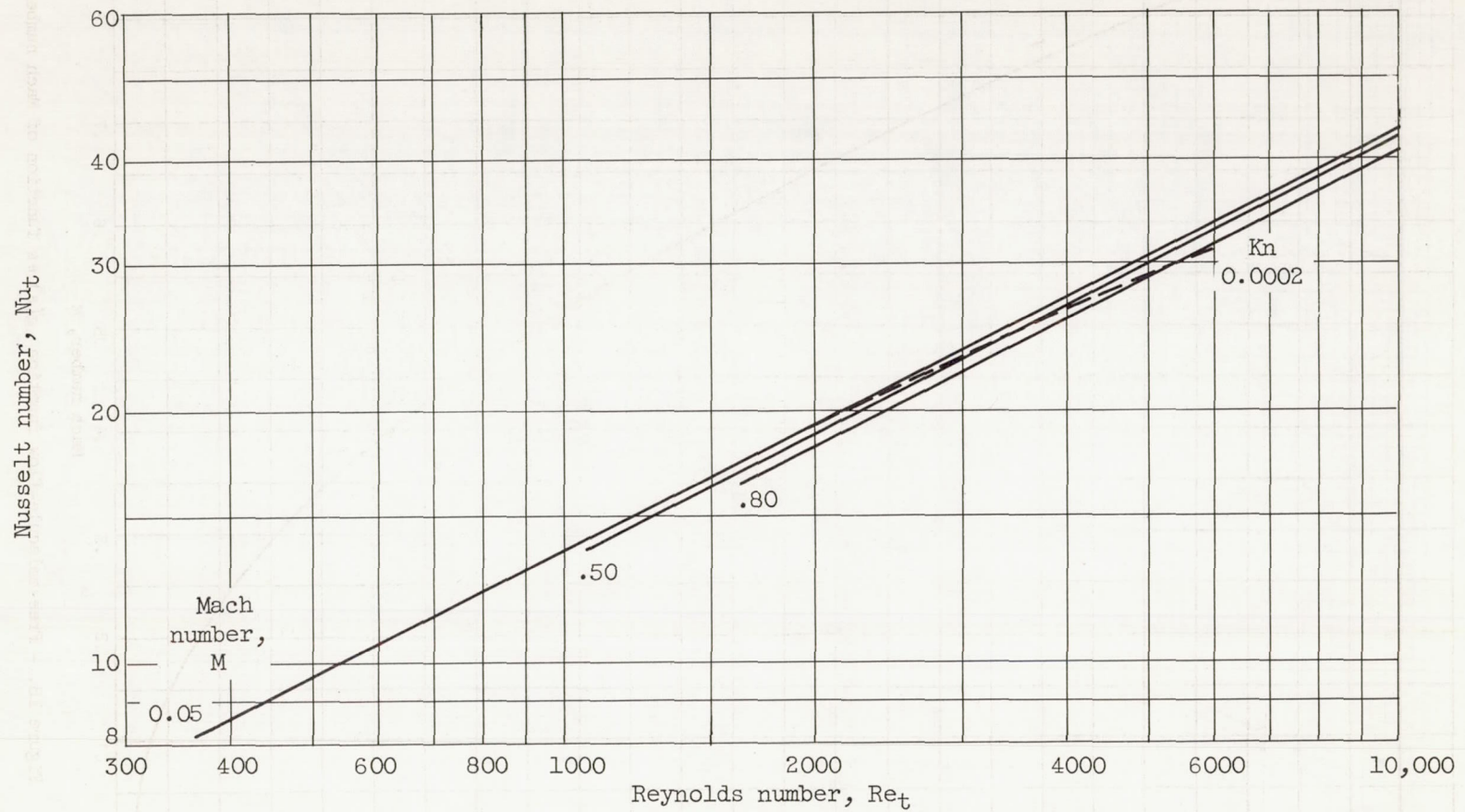


Figure 17. - Continuum-flow experimental Nusselt number correlation (after ref. 13).

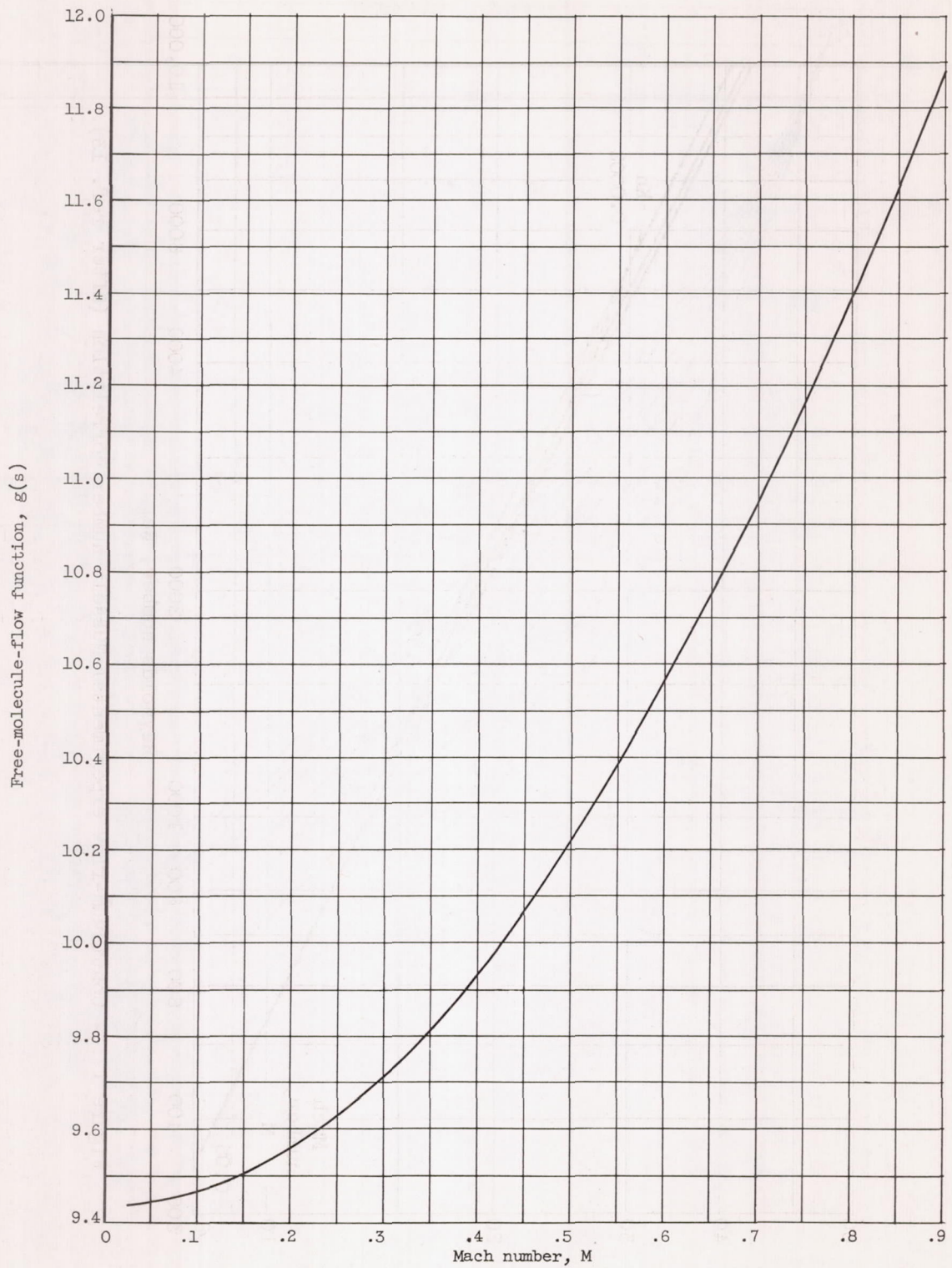


Figure 18. - Free-molecule-flow function $g(s)$ as function of Mach number.

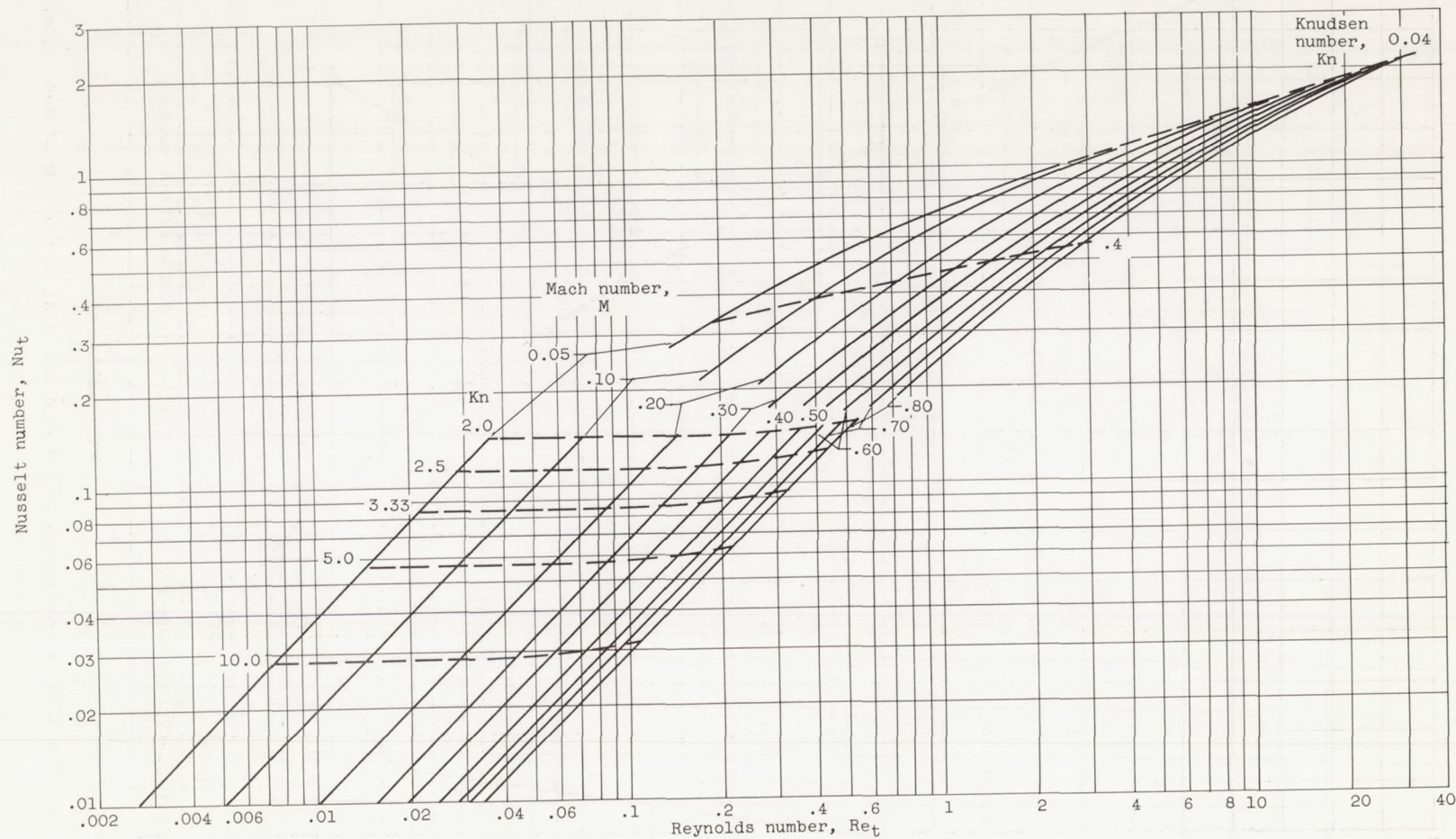
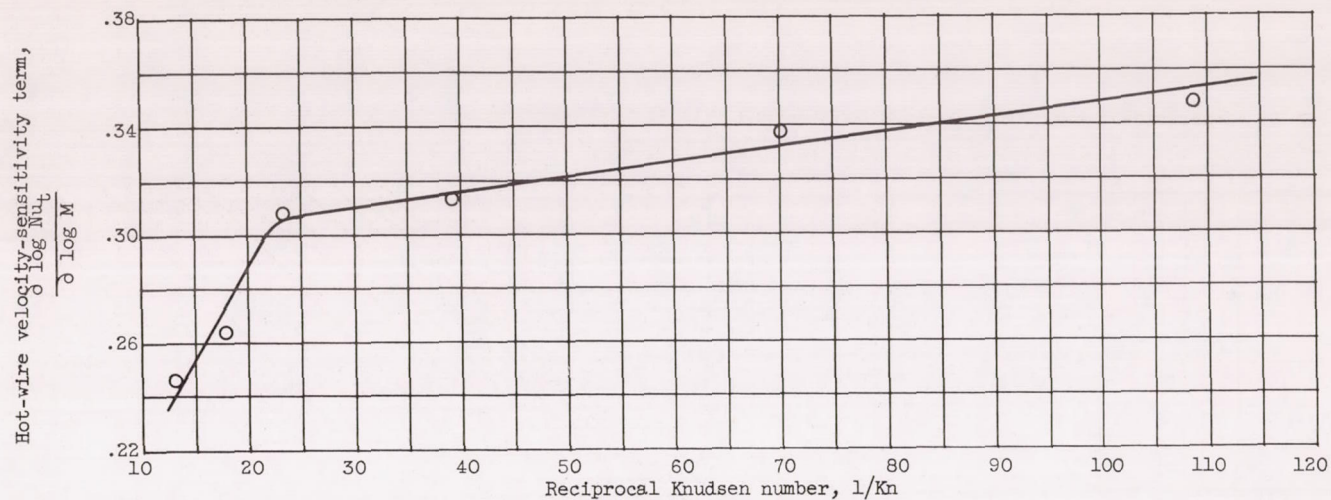
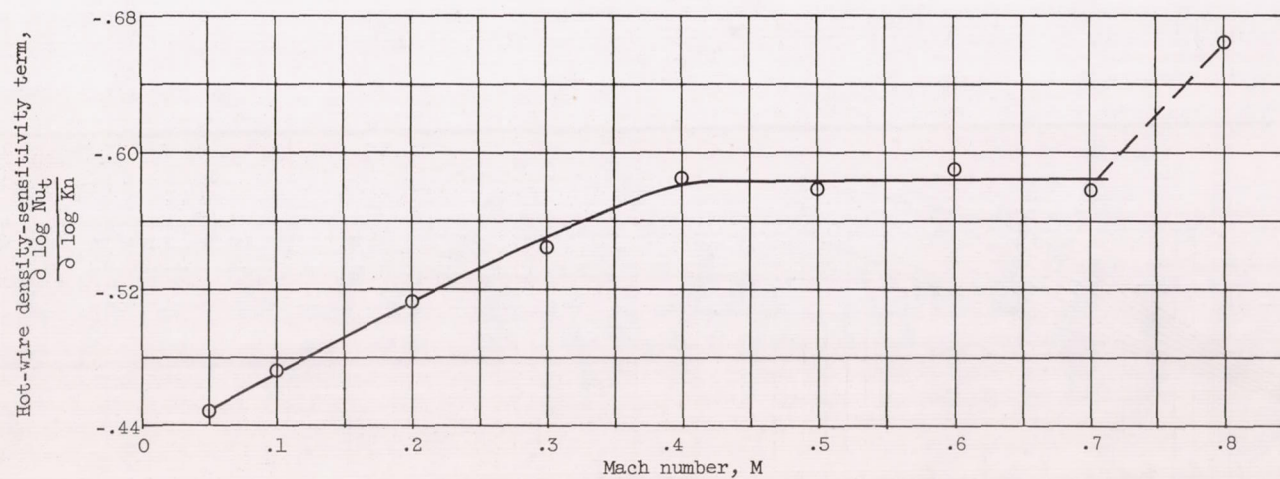


Figure 19. - Comparison of approximate slip-flow theory with free-molecule-flow prediction.



(a) Velocity sensitivity: $0.05 < M < 0.40$.



(b) Density sensitivity: $0.009 < Kn < 0.077$.

Figure 20. - Hot-wire sensitivity terms. Restrictions: $T_t = 80^\circ \text{F}$; $T_w - T_e > 200^\circ \text{F}$.

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